



NOTE ***
PRELIMINARY REVIEW
DRAFT ONLY

Heliophysics

THE SOLAR AND SPACE PHYSICS OF A NEW ERA

Recommended Roadmap for
Science and Technology 2009–2030

2009 Heliophysics Roadmap Team
Report to the NASA Advisory Council
Heliophysics Subcommittee
May 2009

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heliophysics

What Causes the Sun to Vary?

How do the Earth and Heliosphere Respond?

What are the Impacts on Humanity?



Heliophysics

THE SOLAR AND SPACE PHYSICS OF A NEW ERA

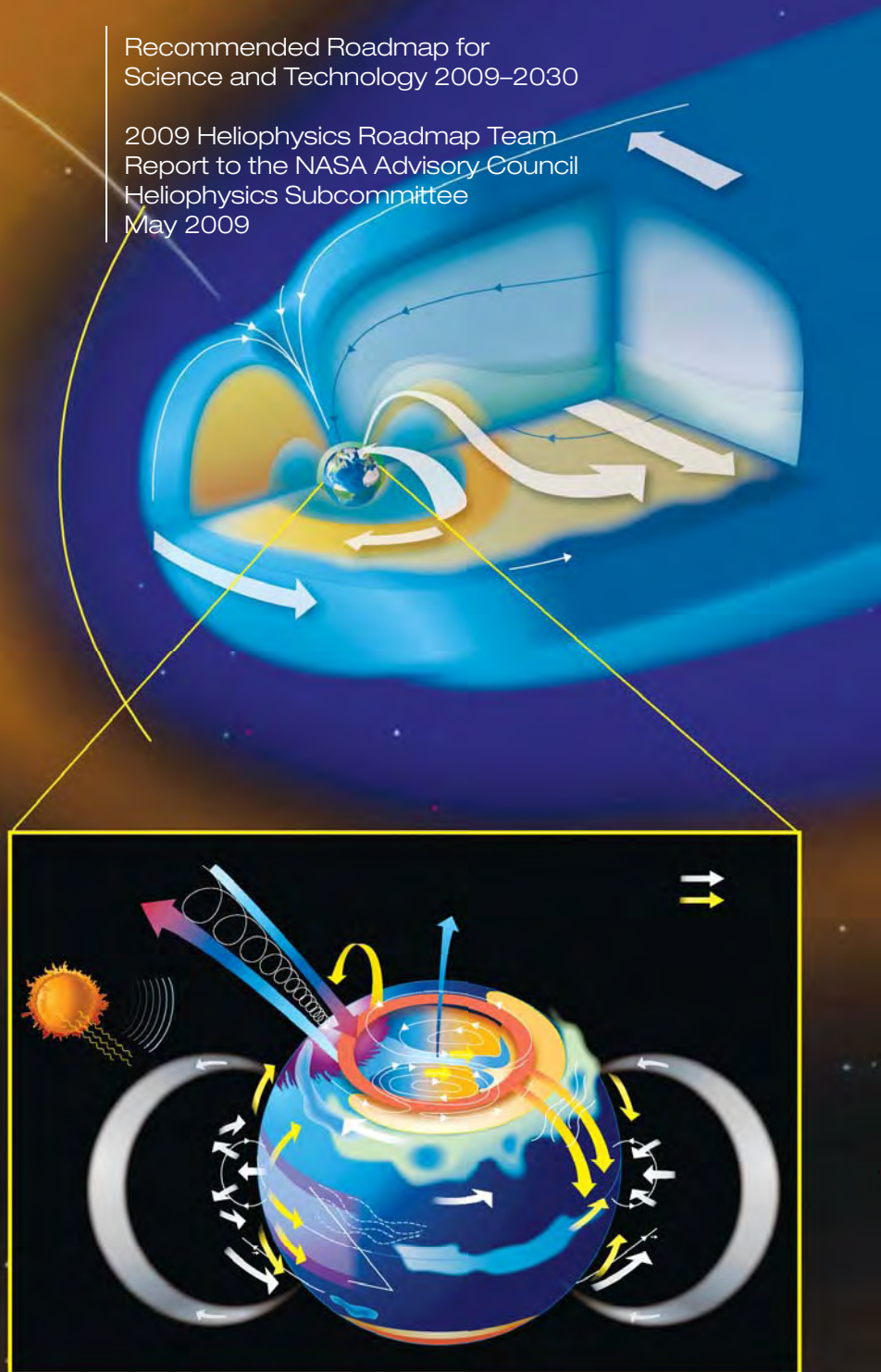
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Cover Image Caption:

Heliophysics is a science that studies the linked phenomena in the region of space influenced by the Sun. It seeks to understand the influence of the Sun throughout the solar system and, in particular its connection to the Earth and the Earth's extended space environment. Key in this endeavor is the study of the fourth state of matter: plasma. A plasma is a conducting body of electrically charged electrons and ions. In space, plasmas are controlled by the gravitational and magnetic fields of the Sun and the bodies within the solar system. Plasma processes are expressed in the Sun, the Sun's atmosphere, interplanetary and interstellar space, and in planetary magnetospheres and ionospheres. The aurora is a widely known, visible manifestation of plasma processes at Earth. Ultimately, the habitability of the Earth is governed by the sum total of such gravitational and magnetically controlled events in the evolution of the solar system.



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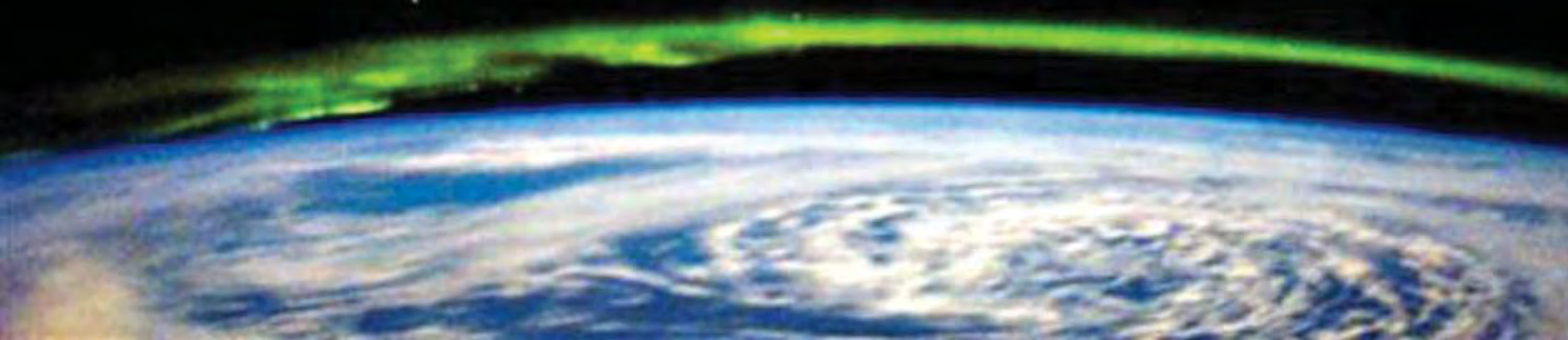
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The drive to understand the world around us is a basic part of our humanity. Research in fundamental science provides the ideas and discoveries that form the long-term foundation for science and technology as a whole, which in turn drive the global economy and our very way of life. In 2005, a panel of nationally recognized experts from across the spectrum of science and society, chaired by Norman Augustine, retired chairman and chief executive officer, Lockheed Martin Corporation, produced "Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future." To quote from the report:

"The growth of economies throughout the world has been driven largely by the pursuit of scientific understanding, the application of engineering solutions, and the continual technological innovation. Today, much of everyday life in the United States and other industrialized nations, as evidenced in transportation, communication, agriculture, education, health, defense, and jobs, is the product of investments in research and in the education of scientists and engineers..."



Executive Summary

Solar and Space Physics in a New Era

Our planet is immersed in a seemingly invisible yet exotic and inherently dangerous environment. Above the protective cocoon of Earth's lower atmosphere exists a highly variable mix of electrified and magnetized matter intertwined with penetrating energetic radiation and extremely fast atomic-sized particles. This environment is created by the interaction of the Earth's magnetic field with the outer atmosphere of our star, the Sun. The Sun's output of energy varies on time scales from seconds to years and forms its own complex magnetic field structure that stretches throughout the solar system. It controls the entry of cosmic rays into the solar system and drives some of the largest changes in the environment affecting our atmosphere, ionosphere, and potentially our climate. This extended atmosphere of the Sun reaches far beyond the orbit of Pluto and affects all planetary bodies in the solar system. It moves through our Milky Way galaxy where it is influenced by slowly changing interstellar conditions that in turn could have consequences for habitability on Earth. This immense volume is our cosmic neighborhood; it is the domain of the science called Heliophysics.

Heliophysics is the science that includes all aspects of the research needed to understand the Sun and its effects on the Earth and the solar system. Because the phenomena and connections between these systems cannot yet be fully explained or adequately predicted, a robust program of discovery and integration of knowledge across the domain is addressed here. The ultimate goal of our effort is to study the Sun, the Heliosphere, and planetary environments as elements of a single interconnected system, one that contains dynamic space weather and evolves in response to solar, planetary, and interstellar conditions.

This document represents an input of the U.S. Heliophysics science community into the NASA Science Directorate strategic planning process for the period 2009–2030. The Roadmap Team was charged by NASA Headquarters to craft a sustainable science program that would be achievable within the resources provided to NASA for this purpose. We hope you find this to be a useful and flexible strategic plan capable of guiding the implementation of this science discipline so vital to our Nation's space program.

Flexibility was a guiding principal as the Roadmap Team developed the Roadmap. We wanted a plan that would enable first-rate science, including flexibility that provides for new discoveries and partnership opportunities; a plan with built-in resilience against uncertainties brought about by changes in the available funding and implementation cost, and limits in launcher availability. A primary consideration was to maintain a healthy launch cadence so as to scientifically address the end-to-end system.

This roadmap articulates a paradigm change by presenting a prioritized science queue with a recommendation to defer specific mission implementation approaches until the time of mission formulation. The science queue was constructed to be consistent with the current (FY 2009) budget profile. By presenting a science queue rather than a mission queue, and deferring definition of detailed mission archi-

Image Caption:

In this image provided by NASA a STS-123 Endeavour crewmember captured the glowing green beauty of the Aurora Borealis while docked and onboard the International Space Station. Looking northward across the Gulf of Alaska, over a low pressure area (cloud vortex), the aurora brightens the night sky. This image was taken on March 21, 2008 at 9:08:46 (GMT) 5:08:46 EDT with a 28 mm lens from the nadir point of 47.9 degrees north latitude and 146.8 degrees west longitude. (AP Photo/NASA)

tures until formulation, the roadmap emerges as a true strategic plan. Specific mission architectures are the implementation tactics to be determined within the context of constraints at hand.

A plan emerges with the best potential to achieve the vision for Heliophysics set forth in the 2003 National Research Council (NRC) Decadal Survey. This Roadmap also highlights the roles and interdependence of the several Heliophysics program elements—the funded mission lines—including how they should be utilized to achieve a unified understanding of the interconnected phenomena that characterize our cosmic neighborhood.

The team determined that significant progress requires understanding of both the laws of basic space plasma physics and the way in which these basic laws are coupled over a vast variety of temporal and spatial scales. Developing a detailed understanding of these systems is the primary challenge for solar and space physics for the new era ahead. The team also determined that it is time for a strategic commitment to systems science, which is an approach to understanding the natural and physical world with a recognition as to how individual phenomena are interconnected. System science recognizes that it is virtually impossible to understand complex phenomena without understanding how it affects and is affected by internal and external processes. System science demands a deep understanding of fundamental processes, and at the same time, development of concepts that integrate knowledge across disciplinary boundaries.

These basic truths motivate and distinguish our program elements and specifically our mission lines. The Solar Terrestrial Probes (STPs) strategic mission line addresses the fundamental processes behind the basic laws of space plasma physics and the Living With a Star (LWS) line is dedicated to studying the system science most relevant to life and society.

In concert with the other NASA science divisions (Planetary Science, Astrophysics, and Earth Science), we share the responsibility for the scientific exploration and understanding of the Earth, our solar system, the universe, and their interrelationships. Heliophysics brings to the table the ability to directly sample the local cosmic environment, which is not unlike that of many stellar systems in the universe. This is our only hands-on astrophysical laboratory. Here, we obtain knowledge about phenomenon that shapes a solar system and that has the potential to lead to the habitability of a planet. On Earth, we enjoy a beautiful and mild climate as contrasted to the desolation of Mars or the fiery-furnace climate of Venus. The U.S. scientific community has committed to a long-term, sustained effort toward understanding these complex and perplexing scientific problems. We can imagine a future in which we have an understanding exemplified by predictive models of the Sun-Earth-planet system and consistent with all areas of space science.

The realization of these goals will be accomplished by studying the Heliospheric system, one that contains dynamic space weather and evolves in response to solar, planetary, and interstellar conditions. Focused research programs addressing specific space environmental hazards will help guide the design and operation of safe and productive missions. Concurrently, we will pursue a deeper understanding of the fundamental physical processes that underlie the awe-inspiring phenomena of space. *Such an understanding is not only one of the more important intellectual accomplishments for our times, but it also provides knowledge and predictive capabilities essential to future human and robotic exploration of space to fulfill our destiny to reach beyond the confines of our planet and navigate the ocean of space.*

Forward progress hinges on the acquisition of new observations and thus new space missions. Within the Heliophysics Division, several important missions are under development with launches planned in the near future. This roadmap strongly endorses the acquisition and launch of these missions. The first, the Solar Dynamics Observatory, is scheduled for launch this year to understand the fundamental nature of the solar dynamo and how it produces the solar cycle. The Radiation Belt Storm

Probes will explore the processes that control the acceleration of space plasma to hazardous levels. Magnetospheric Multiscale will seek to understand the fundamental process of magnetic reconnection, which taps the energy stored in a magnetic field and converts it to heat and kinetic energy. These missions will be followed by Solar Probe + that will orbit closer to the Sun than any previous spacecraft to discover why the solar corona is so much hotter than the photosphere and how the solar wind is accelerated. The Solar Orbiter collaborative mission with ESA will explore the magnetic structure of the Sun-Heliosphere system.

A set of six new and exciting science targets are recommended. These targets will become the basis for critical, cost-constrained missions as new additions to the Heliophysics System Observatory (HSO) constellation. They will address the most urgent and compelling science issues across the field.

Three of the targets address fundamental processes and were assigned to the Solar Terrestrial Probe mission line; the others address significant interconnection science issues and were assigned to the Living With a Star mission line. All are to be scoped to fit within the NASA small or medium cost category. The cost of individual missions is to be constrained to these categories—as defined by NASA NPR7120—so as to meet the launch cadence recommendation. This compromise on individual mission scope is intended to enable a deployment of assets frequently enough to address the entire range of most urgent scientific problems and advance the system level understanding of Heliophysics.

The highest priority targets and the principal science questions to be addressed are as follows:

Solar Terrestrial Probes Science Queue

- **Origins of Near Earth Plasma (ONEP):** Understand the origin and transport of terrestrial plasma from its source to the magnetosphere and solar wind.
- **Solar Energetic Particle Acceleration and Transport (SEPAT):** Understand how and where solar eruptions accelerate energetic particles that reach the Earth.
- **Ion-Neutral Coupling in the Atmosphere (INCA):** Understand how neutral winds control ionospheric variability.

Living With a Star Science Queue

- **Climate Impacts of Space Radiation (CISR):** Understand our atmosphere's response to auroral, radiation belt, and solar energetic particles, and the associated effects on ozone.
- **Dynamic Geospace Coupling (DGC):** Understand how magnetospheric dynamics provides energy into the coupled ionosphere-magnetosphere system.
- **Heliospheric Magnetism (HMag):** Understand the flow and dynamics of transient magnetic structures from the solar interior to Earth.

This implementation strategy assumes the continued support of the existing space assets of the HSO and the availability of timely Explorer Program missions. In addition, to realize the full potential of the space assets, the strategy must be undergirded by a robust foundation of supporting research, data analysis, modeling and theory, and technology development. The product of the combined effort will be new knowledge and an understanding of the realm of Heliophysics that brings economic and intellectual benefits to our Nation.

Additionally, the multidisciplinary nature of the science demands flights across a broad range of targets, which in turn requires a timely launch frequency. Our strategy calls for a launch cadence of two to three per decade in each of the STP and LWS mission lines to advance a system level understanding of Heliophysics. The cost growth in individual missions must be contained to meet these launch cadence

requirements. The Roadmap Team has prioritized the science queue based on a cost box and we do not recommend meeting the science of these targets at any cost. The need for setting achievable project requirements for future missions, managing effectively and containing cost growth are critical to success.

Summary of Recommendations

- This roadmap recommends implementation of a science target queue to address the most urgent Heliophysics science problems facing the Nation.
- This roadmap recommends that peer review competition be used to scope the implementation of strategic missions to best address the recommended science goals within the resources available.
- This roadmap recommends that the time span between mission definition and procurement be minimized. Procure what is planned and implement what is procured.
- This roadmap recommends that policies and procedures be implemented to minimize and control implementation costs during all phases of mission formulation and development. Avoid a “mission regardless of cost” mentality.
- This roadmap recommends that NASA strive to meet a launch frequency that allows the entire range of most urgent scientific problems to be addressed and advances a system level understanding of Heliophysics.
- This roadmap recommends that policies and procedures which facilitate and promote research activities to gain understanding of the system be implemented.
- This roadmap encourages continuation of the existing NASA efforts that transition new scientific knowledge in Heliophysics to operational use by other agencies and institutions.
- This roadmap recommends that existing NASA Research and Analysis (R&A) programs be utilized to support the technology development projects needed to implement the new science targets.

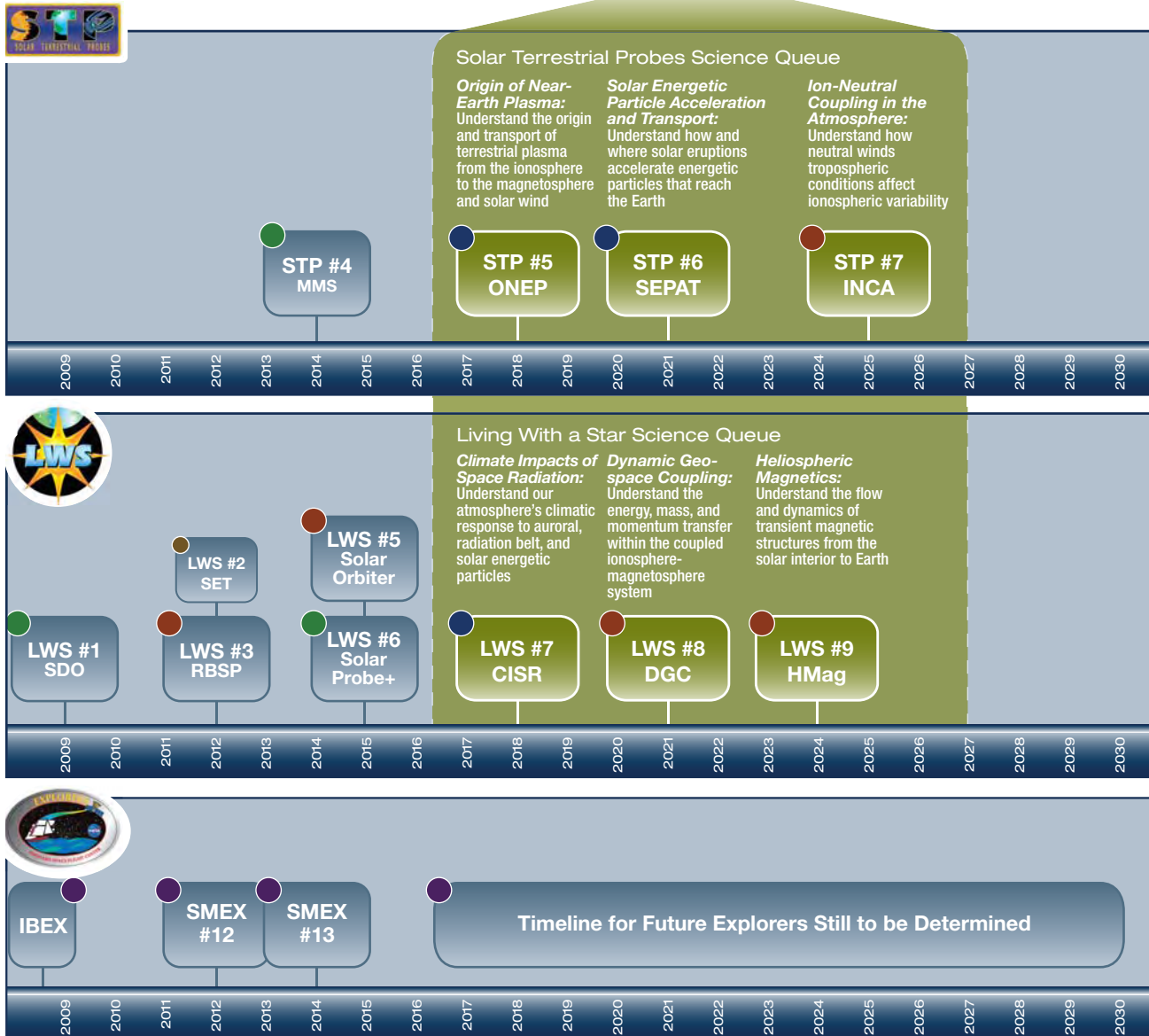
Heliophysics has an operating fleet of spacecraft observing the phenomena of interplanetary space, a set of highly functional missions in development positioned to provide vital new insights, and a fresh strategy for exciting new discoveries in space physics. Our work of the past decade has answered important questions about the physics of the Sun, the interplanetary medium, and the space environments of Earth and other solar system bodies. Our research has also highlighted areas of uncertainty where understanding is seriously lacking.

We have formulated a plan intended to address the most pressing of the open science issues, with sufficient flexibility to execute the plan within NASA resources. The science targets will take us on a journey deep into the physics of magnetized plasma transport and energization across the vastness of space from the Sun to our own magnetosphere and ionosphere, and then to the further reaches of the solar system. Throughout, we will confront the fundamental processes upon which the behavior of the whole is built. We will expand our vision of the connection between what happens in space and how our home in space is affected. Another set of targets will expand our vision of the connections between what happens in space and how it affects our home in space. The variability of the Sun’s output of energy has direct consequences on Earth. It certainly has an impact on the space environment. It may even have an impact on our climate.

We are optimistic that the new targets recommended with this strategic plan will advance science in a manner beneficial to our Nation. We hope you will join us as we move forward toward a comprehensive description and understanding of the Heliophysics domain.

Science queue for Heliophysics mission lines 2009–2030. Missions awaiting launch and those in formulation/development are shown with current mission names. New strategic science targets are identified by their science objective and centered on anticipated launch dates. Explorer launches are indicated; specific science content will be competed. Potential partnership and leveraged missions are also indicated. Within currently known implementation assumptions and constraints, this queue is achievable within the President's FY 2009 budget.

Recommended Science Queue



Cost Definitions for Missions:

- Nominal
- Light: <\$250M
- Small: \$250M–\$500M
- Medium: \$500M–\$750M
- Large: \$750M–\$1B

Per NPR 7120.5 D

Potential International Partnerships

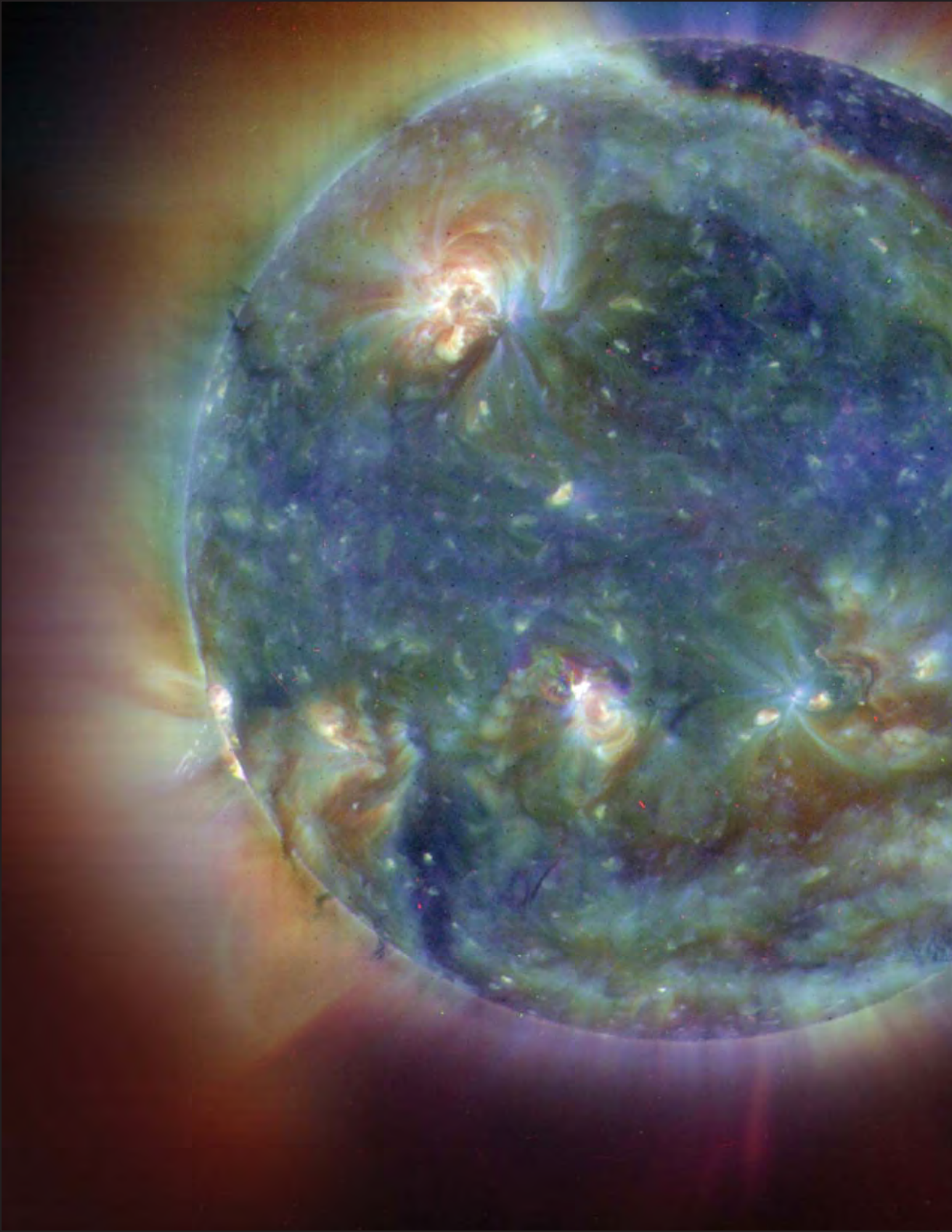
- SOLAR-C (JAXA)
- ORBITALS (CSA)
- Cross-Scale/Scope (ESA/JAXA)
- Interstellar Probe

Color indicates NASA contribution not reflected in roadmap budgeting—would require additional resources

Intra-NASA Partnerships

- JUNO
- Mars Atmosphere and Volatile Evolution (MAVEN)
- Mars Science Laboratory (MSL)
- Lunar Reconnaissance Orbiter (LRO)
- Lunar Atmosphere and Dust Environment Explorer (LADEE)

No contribution of funds anticipated





Chapter I

HELIOPHYSICS: THE SCIENCE

The science of Heliophysics seeks understanding of the interaction of the large complex, coupled system comprising the Sun, Earth, and Moon, other planetary bodies, the vast space within the solar system, and the interface to interstellar space. Heliophysics is a bold enterprise of space exploration that seeks to understand the connections that govern the solar system and the implications for our home in space, to predict the hazards of exploration, and to understand the impact of the space environment for the habitability of other worlds.

NASA has charged the Heliophysics Division to “develop an understanding of the Sun and its Effects on Earth and the Solar System.” Working from this directive, the formulation of a strategy for Heliophysics research begins with a clear exposition of the scientific goals that flow from this and other NASA and national high-level goals. In Chapter 1, we address the science in three broad and interconnected scientific and exploration objectives:

- **Open the Frontier to Space Environmental Prediction.**
- **Understand the Nature of Our Home in Space.**
- **Safeguard the Journey of Exploration.**

Each objective is comprised of Research Focus Areas (RFA) from which Priority Investigations are derived. The RFAs are mapped to the Challenges articulated in the NRC 2003 Heliophysics Decadal Survey.

The thread of systems science runs through each of these and serves to emphasize the importance of deep, intensive investigations of fundamental physical processes encompassing a cross section of disciplinary boundaries and intellectual constructs and scientific theories that provide an integrated understanding of how the system works as a whole.

Understand the Sun and its Effects on Earth and the Solar System



Open the Frontier to Space Environmental Prediction

Understand the fundamental physical processes of the space environment—from the Sun to Earth, to other planets, and beyond to the interstellar medium.



Understand the Nature of our Home in Space

Understand how human society, technological systems, and the habitability of planets are affected by solar variability interacting with planetary magnetic fields and atmospheres.



Safeguard the Journey of Exploration

Maximize the safety and productivity of human and robotic explorers by developing the capability to predict the extreme and dynamic conditions in space.

Research Focus Areas

- F1** Magnetic reconnection
- F2** Particle acceleration and transport
- F3** Ion-neutral interactions
- F4** Creation and variability of magnetic dynamos

Open the Frontier to Space Environmental Prediction

The Sun, our solar system, and the universe consist primarily of plasma. Plasmas are more complex than solids, liquids, and gases because the motions of electrons and ions produce both electric and magnetic fields. The electric fields accelerate particles, sometimes to very high energies, and the magnetic fields guide their motions. This results in a rich set of interacting physical processes, including intricate exchanges with the neutral gas in planetary atmospheres.

Although physicists know the laws governing the interaction of electrically charged particles, the collective behavior of the plasma state leads to complex and often surprising physical phenomena. As the foundation for our long-term research program, we will develop a comprehensive scientific understanding of the fundamental physical processes that control our space environment.

The processes of interest occur in many locations, though with vastly different magnitudes of energy, size, and time. By quantitatively examining similar phenomena occurring in different regimes with a variety of techniques, we can identify the important controlling mechanisms and rigorously test our developing knowledge. Both remote sensing and in situ observations will be utilized to provide the complementary three-dimensional, large-scale perspective and the detailed small-scale microphysics view necessary to see the complete picture.

Research Focus Areas

- H1** Causes and evolution of solar activity
- H2** Earth's magnetosphere, ionosphere, and upper atmosphere
- H3** Role of the Sun in driving change in the Earth's atmosphere
- H4** Apply our knowledge to understand other regions

Understand the Nature of our Home in Space

Humankind does not live in isolation; we are intimately coupled with the space environment through our technological needs, the solar system bodies we plan to explore, and ultimately the fate of our Earth itself. We regularly experience how variability in the near-Earth space environment affects the activities that underpin our society. We are living with a star.

We plan to better understand our place in the solar system by investigating the interaction of the space environment with the Earth and the effect of this interaction on humankind. We plan to characterize and develop a predictive knowledge of the impact of the space environment on our planet, technology, and society. Our goal is to understand the web of linked physical processes connecting Earth with the space environment.

We are increasingly interested in the planetary environments that await us and how the lessons learned can be applied to our home on Earth. Much can be learned by studying our own atmosphere and applying that knowledge to the exploration of other planets. Even a casual scan of the solar system is sufficient to discover that habitability, particularly for humankind, requires a rare confluence of many factors. At least some of these factors, especially the role of magnetic fields in shielding planetary atmospheres, are subjects of immense interest.

Research Focus Areas

- J1** Variability, extremes, and boundary conditions
- J2** Capability to predict the origin, onset, and level of solar activity
- J3** Capability to predict the propagation and evolution of solar disturbances
- J4** Effects on and within planetary environments

Safeguard the Journey of Exploration

NASA's robotic spacecraft continue to explore the Earth's neighborhood and other targets in the heliosphere. Humans are expected once again to venture onto the surface of the Moon and one day onto the surface of Mars. This exploration brings challenges and hazards. We plan to help safeguard these space journeys by characterizing, understanding, and developing forecasting strategies for space environmental hazards.

This work will aid in the optimization of habitats, spacecraft, and instrumentation, and for planning mission operation scenarios, ultimately increasing mission productivity. We will analyze the complex influence of the Sun and the space environment, from origin to the destination, on critical conditions at and near exploring human and robotic spacecraft. Collaborations between Heliophysics scientists and the entities preparing for human and robotic exploration will be fostered through interdisciplinary research programs and the common use of NASA research assets in space.



Open the Frontier:

Understand magnetic reconnection as revealed in solar flares, coronal mass ejections, the solar wind, and in magnetospheres

Reconnection is a topological change in a magnetic field configuration that releases stored magnetic energy to a plasma. Reconnection can accelerate particles to very high energies and, it can dramatically alter the regions of space accessible to those particles. It is responsible for the energy release in solar flares. In the corona, reconnection can sever large clouds of dense plasma from the magnetic fields that anchored them. Reconnection at the front side of the magnetosphere and in the magnetotail is responsible for the coupling between the solar wind and the Earth's magnetosphere that drives the aurora and geomagnetic storms. The consequences of reconnection can be devastating to space assets, voyaging humans, and communication systems on Earth.

Reconnection is fundamentally a multiscale process. The large-scale configuration of the magnetic field creates the conditions under which reconnection can occur, but the explosive conversion of magnetic energy originates in a region called the diffusion region that is very small in comparison. For example, reconnection at the Earth's magnetopause (the boundary separating the solar wind and terrestrial magnetic fields) occurs in a region with an area on the order of hundreds of square kilometers, compared to a total magnetopause surface area of approximately 60 billion square kilometers. Current solar imaging techniques are insufficient to resolve the diffusion region associated with solar flares and coronal mass ejections (CMEs). While there have been a few encounters with the diffusion region in the near-Earth environment, systematic study of this phenomenon is just beginning. The physical processes that initiate and control reconnection remain to be measured.

Most of our basic theoretical understanding of reconnection comes from a magnetohydrodynamics (MHD) perspective. Although this approach has provided important insight, it is inherently limited in that it cannot predict the very small scales on which ions and electrons decouple from the magnetic field or the detailed particle energization process. Important questions remain unanswered both observationally and theoretically: What initiates the reconnection process? What are the kinetic processes that occur and what is their role? What is the range of scale sizes of the region over which reconnection occurs in different regimes? What determines if reconnection is quasi-steady or bursty? What mechanisms or boundary conditions control the spatial and temporal scales? What is the three-dimensional structure of the reconnection region and how does this structure affect particle acceleration?

Priority Investigations:

What are the fundamental physical processes and topologies of magnetic reconnection?

How are plasmas and charged particles heated and accelerated?

How are mass and energy transferred from the heliosphere to a planetary magnetosphere?

Decadal Survey Challenges:

Challenge 4: Understanding the basic physical principles manifest in processes observed in solar and space plasmas.



Open the Frontier:

Understand the plasma processes that accelerate and transport particles

Priority Investigations:

How are plasmas and charged particles heated and accelerated?

How is solar wind plasma accelerated?

How are planetary thermal plasmas accelerated and transported?

How do solar wind disturbances propagate and evolve through the solar system?

What are the roles of mass and energy flows in the behavior of planetary magnetospheres?

Decadal Survey Challenges:

Challenge 4: Understanding the basic physical principles manifest in processes observed in solar and space plasmas.

Challenge 5: Developing a near-real-time predictive capability for understanding and quantifying the impact on human activities of dynamical processes at the Sun, in the interplanetary medium, and in Earth's magnetosphere and ionosphere.

High-energy particles accelerated at the Sun and within interplanetary space, as well as cosmic rays from outside the solar system, pose a serious hazard to human and robotic exploration. Energetic particles produced or trapped within planetary magnetospheres can have deleterious effects on important technological assets in those locations. Predicting these effects requires a fundamental understanding of where and how particles in space can be accelerated and how they are transported.

More than one mechanism can operate to produce a given energetic particle population at a given location. Moreover, energetic particles are accelerated both at localized sites (solar flares, planetary bow shocks, magnetotail reconnection sites, auroral acceleration regions, and radiation belts), and globally (coronal and interplanetary shocks, co-rotating interaction regions and global merged interaction regions in the solar wind, and the termination shock). Important processes for near-term investigation include quasi-static electric fields parallel to the background magnetic field, wave electric fields, stochastic (Fermi) acceleration, and the drift of particles along a component of the electric field such as that occurs in shocks and the magnetotail.

The Earth's aurora provides a unique opportunity to understand acceleration by parallel electric fields and waves. Particle acceleration at CMEs shock fronts is a leading candidate for the production of gradual solar energetic particle (SEP) events. New observations at the solar wind termination shock suggest that suprathermal ion populations dominate the kinetic energy of the plasma in the heliosheath, which changes our views of how particle energizing occurs in the outer heliosphere.

An understanding of the acceleration of thermal plasmas is also vital as these may form seed populations for subsequent energization, or mediate the transport and acceleration of energetic particles. In terrestrial and planetary magnetospheres, for example, thermal plasmas can be accelerated to sufficiently high energies to form ring currents and radiation belts. The solar wind transports energetic particles, and also provides acceleration regions through its interaction with magnetospheres, the termination shock, stream interaction regions, and interplanetary CMEs. The origin of the solar wind is not well understood and represents a large gap in our knowledge of fundamental processes.



Open the Frontier:

Understand the ion-neutral interactions that couple planetary ionospheres to their upper atmospheres and solar and stellar winds to the ambient neutrals

There are many locations throughout the solar system where interactions between charged and neutral particles strongly affect the behavior of the system. Charged and neutral species respond to different forces but interact through collisions. These collisions result in chemical reactions and transfer energy and momentum between the populations. Most important for near-term study is to understand the large-scale balance between gravitationally and magnetically controlled components of the system.

Planetary atmospheres, including that of the Earth, are affected directly by ultraviolet (UV) and infrared radiation from the Sun. Charged particles are produced when this radiation is absorbed and energy is produced that can be redistributed in a variety of ways before being reradiated to space. The charged particles may also be influenced by a magnetic field. The Sun's interplanetary magnetic field can produce a stress known as mass loading. The presence of a planetary magnetic field prevents direct interaction of an atmosphere with the solar wind and produces a magnetosphere providing additional pathways for redistributing the energy from the Sun.

In the case of Earth, the upper atmosphere is also subject to energy and momentum inputs from below, produced by tropospheric processes and mountainous geographic features. Variations in these inputs can change the large-scale temperature and composition in the middle and upper atmosphere. Such processes may also operate in the atmospheres of Venus and Mars.

When charged and neutral particles exist in the presence of a magnetic field, the mobility of the magnetized plasma becomes anisotropic and drag forces between the plasma and the neutral gas produce complex electrodynamic interactions. Such interactions dramatically affect the spatial distribution of the plasma, and the resulting instabilities lead to structures spanning a wide range of sizes. In the case of the Earth, large-scale plasma structures accelerate or decelerate the neutral atmospheric gases and change circulation patterns. Smaller scale plasma structures influence the propagation of radio waves and affect communications and navigation systems.

These and other interactions between charged and neutral species feed the non-linear, seemingly individual behavior of both species. It is not possible to specify the state of the entire system from only instantaneous knowledge of a single component or from simple monitoring of external drivers. Rather, both initial states and the evolutionary time scales must be understood over a wide spectrum of scales. Meeting these requirements represents our primary challenge to future progress.

Priority Investigations:

What governs the coupling of neutral and ionized species?

How do coupled middle and upper atmospheres respond to external drivers and to each other?

What is responsible for the dramatic variability in many of the state variables describing the ITM region?

How do the magnetosphere and the ionosphere-thermosphere systems interact with each other?

How do the heliosphere and the interstellar medium interact?

Decadal Survey Challenges:

Challenge 2: Understanding heliospheric structure, the distribution of magnetic fields and matter throughout the solar system, and the interaction of the solar atmosphere with the local interstellar medium.

Challenge 3: Understanding the space environments of Earth and other solar system bodies and their dynamical response to external and internal influences.

Challenge 4: Understanding the basic physical principles manifest in processes observed in solar and space plasmas.



Open the Frontier:

Understand the creation and variability of magnetic dynamos and how they drive the dynamics of solar, planetary, and stellar environments

Priority Investigations:

How do planetary dynamos function and why do they vary so widely across the solar system?

What is the fundamental nature of the solar dynamos and how does it produce the solar cycle?

What are the precursors to solar disturbances?

How are mass and energy transferred from the heliosphere to a planetary magnetosphere?

What is responsible for the dramatic variability in many of the state variables describing the ITM region?

Decadal Survey Challenges:

Challenge 1: Understanding the structure and dynamics of the Sun's interior, the generation of solar magnetic fields, the origin of the solar cycle, the causes of solar activity, and the structure and dynamics of the corona.

Challenge 3: Understanding the space environments of Earth and other solar system bodies and their dynamical response to external and internal influences.

Challenge 4: Understanding the basic physical principles manifest in processes observed in solar and space plasmas.

The generation of cosmic magnetic fields is a fundamental physical mystery that underlies a wide range of phenomena in the Sun-Earth system, the solar system, and indeed the universe beyond. In addition, magnetic fields control and influence many events that affect the technological functions of our society.

For example, the Sun's variable magnetic field is the energy source for solar particle acceleration and the structure of the field controls the entry of galactic cosmic rays (GCRs) into the solar system as well as the strength of geomagnetic storms. Helioseismic data from the Solar and Heliospheric Observatory (SOHO) and ground-based observatories have revolutionized dynamo theories of magnetic field generation by placing the main solar cycle dynamo action at the base of the convection zone, in the rotationally sheared layer known as the tachocline. Estimates of the correct characteristics of the meridional circulation are thought to be key ingredients for determining the length of the solar cycle. Recently, models have been created that use the meridional flow patterns from previous cycles to estimate the length and amplitude of the next cycle. However, while these dynamo models may be able to forecast the cycle length, there is some indication that they may not capture all of the relevant physics as the onset of cycle 24 may not agree with the predictions. In addition, details, such as whether the cycle will be double peaked, are still not within our predictive capability. We know even less about activity cycles on other stars, though comparative stellar dynamo studies should reveal much about the long-term behavior of stars and the Sun. Developing the understanding of the dynamo process to enable this kind of prediction is important for long-term planning for solar activity and would have obvious applications in trying to understand past and future periods of abnormal solar activity and concomitant affects on terrestrial climate and planetary habitability.

Closer to home, magnetic reversals and other large variations of the Earth's magnetic field can lead to periods of reduced protection from the harsh radiation environment of space. The process responsible for the existence and behavior of these magnetic fields—again, the dynamo—involves the twisting and folding of weak fields so as to change and amplify them. Solving the problem of just how dynamos operate in such widely different environments, from the liquid metal of planets to the gaseous plasma of stars, will allow better predictions of the effects of magnetic field changes at both the Earth and the Sun. This understanding is essential to describing the coupled Sun-solar system connection and has important implications for the exploration of our solar system.



Our Home in Space:

Understand the causes and subsequent evolution of solar activity that affects Earth's space climate and environment

The climate and space environment that affects Earth are determined by the plasma, particle, and electromagnetic radiation outputs from the Sun. The solar output varies on many time scales: from explosive reconnection on scales of microseconds, to convective turnover taking minutes to hours, to solar rotation over a month, to the 22-year solar magnetic cycle, and to century-long irregular fluctuations, such as the Maunder minimum. This high degree of variability is a consequence of the emergence of the magnetic field from below the photosphere, its transport and destruction on the solar surface, and the intermittent eruption into the heliosphere of energy stored in the atmosphere as flares and CMEs. The heliosphere also modulates the propagation of incoming galactic cosmic rays on large spatial scales that are on the order of the size of the solar system. In addition, longer term changes that can affect Earth's climate include variations in the solar total and spectral irradiance.

As the solar wind is emitted from the edges of coronal holes, it carries embedded fluctuations of magnetic field, density, and temperature, as well as energetic particle populations. All of these phenomena evolve as they travel through the heliosphere. Shocks accelerate the particles and interact with the other irregularities. CMEs can interact with each other. Particles collide and redistribute energy. The result is an ever-changing background of electric fields, magnetic fields, and charged particle radiation bombarding the Earth and near-space environment. Currently, observations of this complex situation are available primarily from near-Sun and 1 AU observations. Understanding the three-dimensional, time-varying propagation of solar disturbances is one of the greatest challenges facing us. Understanding the internal configuration of the structures is another.

Precursors can provide useful information about solar and interplanetary events; however, more complete predictive models based on physical principles are necessary if we are ever to usefully assimilate the information. As with terrestrial weather, it is not yet clear how long in advance solar activity can be predicted. Improved and continuous observations of the solar vector magnetic field, along with high-resolution multispectral observations of the atmosphere are as critical for resolving this question as helioseismology is for revealing the subsurface conditions.

Priority Investigations:

What are the fundamental physical processes and topologies of magnetic reconnection?

What are the precursors to solar disturbances?

How do solar wind disturbances propagate and evolve through the solar system?

How do the heliosphere and the interstellar medium interact?

Decadal Survey Challenges:

Challenge 1: Understanding the structure and dynamics of the Sun's interior, the generation of solar magnetic fields, the origin of the solar cycle, the causes of solar activity, and the structure and dynamics of the corona.



Our Home in Space:

Understand changes in the Earth's magnetosphere, ionosphere, and upper atmosphere to enable specification, prediction, and mitigation of their effects

Priority Investigations:

How are planetary thermal plasmas accelerated and transported?

How are mass and energy transferred from the heliosphere to a planetary magnetosphere?

What are the roles of mass and energy flows in the behavior of planetary magnetospheres?

What is responsible for the dramatic variability in many of the state variables describing the ITM region?

How do the magnetosphere and the ionosphere-thermosphere systems interact with each other?

Decadal Survey Challenges:

Challenge 3: Understanding the space environments of Earth and other solar system bodies and their dynamical response to external and internal influences.

Earth's space environment is a complex, strongly coupled system, energized by an amazing range of inputs that originate with the Sun. One important input is the magnetized solar wind rushing past Earth at a million miles per hour, interacting with Earth's magnetic field to produce the magnetosphere that can accumulate and release that energy in powerful bursts. This process accelerates magnetospheric plasma into Earth's polar regions and heats the upper atmosphere, a well known affect of the aurora. Auroral heating sets the upper atmosphere into motion and modifies its composition and chemistry. Embedded in the atmosphere is the ionosphere, the density of which is usually driven by solar extreme ultraviolet radiation. However, its density can be strongly affected by auroral-induced changes in the atmosphere, and thus by solar wind conditions. The electric fields that develop in the magnetosphere during solar wind-induced disturbances can also strongly modify the ionosphere, drawing high-density plasma from low to high latitudes in great plumes, further enhancing the strength of geomagnetic disturbances by adding to magnetospheric pressure through high-latitude ion outflow.

The short description above shows how solar wind energy initiates a magnetic storm, with subsequent effects in the atmosphere and ionosphere that, in turn, may modify the magnetic storm strength itself. The flow of energy and mass in this strongly coupled system is an intensively studied problem, with broad implications for our technologically advancing society and for basic understanding of plasma processes in planetary environments. Individual parts of the system have been the target of many focused studies, yielding new understanding of processes occurring on a wide range of temporal and spatial scales. Equally important is to understand how these processes couple across the broad range of spatial and temporal scales to our geospace system.

New nonlinear pathways for energy coupling have recently been discovered in geospace. Recent research indicates that the response of the atmosphere to auroral forcing depends not only on the total energy input, but the width of the auroral curtains. Daily tropospheric precipitation in equatorial rainforests releases such a prodigious amount of heat that the tides of atmospheric energy propagating upward from these storms change the ionosphere dramatically. These tides interact with other waves on many scales. These processes involve nonlinear diffusion and wave interactions that are critical for understanding the large-scale behavior of the geospace system.



Our Home in Space:

Understand the role of the Sun and its variability in driving change in the Earth's atmosphere

Solar energy in the form of photons and particles drives the chemical and physical structure of Earth's atmosphere. For example, UV radiation and X-radiation deposited globally throughout the mesosphere and thermosphere are responsible for formation of the ionosphere. Also, while particles primarily deposit their energy at high latitudes, the resulting ionization, dissociation, and excitation of atoms and molecules can have a global effect due to dynamical processes that transport energy. Ultimately, these processes combine to drive the temperature and chemical composition of the entire Earth's atmosphere. A key example of how atmospheric modification by the Sun affects life is stratospheric ozone, which acts as a human UV shield. The very existence of the ozone layer is a direct result of solar energy deposition. Nitric oxide created at higher altitudes by processes involving solar and auroral energy may be transported to lower altitudes where it can destroy ozone. Solar energetic particles have been linked to episodic stratospheric ozone depletions, and it is possible that radiation belt particles play a role as well. Galactic cosmic rays are modulated by the solar cycle, but their possible effects on cloud nucleation and, hence, albedo remains controversial. Because life depends on the atmosphere and its climate, study of solar energy-driven atmospheric variations is critically important. Despite this, the strength and variability of atmospheric solar energy deposition remain poorly understood. In addition, coupling processes that spread effects of energy deposition in altitude and latitude are not well understood. Addressing these issues requires high time-resolution spectral observations of solar energy, measurements of the atmospheric response, as well as theory and modeling of dynamical processes that distribute effects of solar energy.

Priority Investigations:

What governs the coupling of neutral and ionized species?

How do coupled middle and upper atmospheres respond to external drivers and to each other?

How do the magnetosphere and the ionosphere-thermosphere systems interact with each other?

How do long-term variations in solar energy output affect Earth's climate?

Decadal Survey Challenges:

Challenge 3: Understanding the space environments of Earth and other solar system bodies and their dynamical response to external and internal influences.



Our Home in Space:

Apply our knowledge of space plasma physics to understand other regions of the solar system, stars, and the galaxy

Priority Investigations:

What are the fundamental physical processes and topologies of magnetic reconnection?

How are plasmas and charged particles heated and accelerated?

How do planetary dynamos function and why do they vary so widely across the solar system?

What is the fundamental nature of the solar dynamo and how does it produce the solar cycle?

What is the composition of matter fundamental to the formation of habitable planets and life?

Decadal Survey Challenges:

Challenge 2: Understanding heliospheric structure, the distribution of magnetic fields and matter throughout the solar system, and the interaction of the solar atmosphere with the local interstellar medium.

Challenge 3: Understanding the space environments of Earth and other solar system bodies and their dynamical response to external and internal influences.

NRC Astrophysical Context:

Understanding the Sun, heliosphere, planetary magnetospheres and ionospheres as astrophysical objects and in astrophysical context.

Plasmas and their embedded magnetic fields affect the formation, evolution, and destiny of planets and planetary systems. The heliosphere shields the solar system from galactic cosmic radiation. Our habitable planet is shielded by its magnetic field, protecting it from solar and cosmic particle radiation and from erosion of the atmosphere by the solar wind. Planets without a shielding magnetic field, such as Mars and Venus, are exposed to those processes and evolve differently. And on Earth, the magnetic field changes strength and configuration during its occasional polarity reversals, altering the shielding of the planet from external radiation sources.

How important is a magnetosphere to the development and survivability of life? The solar wind, where it meets the local interstellar medium (LISM), forms boundaries that protect the planets from the galactic environment. The interstellar interaction depends on the raw pressure of the solar wind and the properties of the LISM (density, pressure, magnetic field, and bulk flow). These properties, particularly those of the LISM, change over the course of time, and change dramatically on long time scales (1,000 years and longer) as the solar system encounters interstellar clouds. How do these long-term changes affect the sustainability of life in our solar system?

Understanding the nature of these variations and their consequences requires a series of investigations targeting the structure of the heliosphere and its boundaries and conditions in the LISM. Planetary systems form in disks of gas and dust around young stars. Stellar UV emission, winds, and energetic particles alter this process, both in the internal structure of the disk and its interaction with its parent star. The role of magnetic fields in the formation process has not been fully integrated with other parts of the process. The study of similar regions in our solar system, such as dusty plasmas surrounding Saturn and Jupiter, will help explain the role of plasma processes in determining the types of planets that can form, and how they later evolve.



Safeguard the Journey:

Characterize the variability, extremes, and boundary conditions of the space environments that will be encountered by human and robotic explorers

The Sun is a variable star. Beginning with the invention of the telescope more than 400 years ago, it has been found that the Sun shows quasi-periodic behavior in sunspot occurrence, and that the Earth is susceptible to solar variability. The solar activity cycle, linked to sunspots, is approximately 11 years long. Historical records show that not all solar cycles are the same. It is unlikely that the variations we have seen within the 50 years of the space age reflect the full extent of solar variability and extremes. Moreover, computer modeling of the infamous 1859 Carrington event indicates that more severe space weather is possible. It is therefore important to collect long-term records of space weather events and space climate. Even the ongoing and benign solar cycle minimum is unusual compared to all cycles spacecraft have encountered so far: it appears to last longer, and at the same time, the solar polar magnetic field is significantly weaker than in the three previous solar minimum periods. As a result, the Earth's ionosphere has reached its coldest ever state in 2008, and the solar wind output of the Sun, which has waned over the course of past decade seemingly independent of solar activity, has reached a historic low. Recognizing the importance of space measurements, the Heliophysics Division has put in place new rules that will ensure preservation and open access of the data collected by past and currently operating spacecraft. This encompasses that the necessary documentation will be preserved alongside the collected data. Thus, future research into the extremes of the space environment can utilize effectively what this generation of robotic explorers has gathered and how this information fits into the overall context of solar and space environment variability.

The significance of characterizing extremes in Heliophysics derives from its impact on humanity and its dependence on technology. NASA, in particular, develops robotic explorers and plans to send humans past low-Earth orbit, where they are more vulnerable to space weather hazards. A primary hazard to assets and humans in space are energetic particles accelerated at or near the Sun, trapped particles in radiation belts around the Earth (see J4), and galactic cosmic rays. SEPs represent a transient, but high-intensity threat to the safety of astronaut and space hardware. Knowledge of occurrence rate and range of intensities is critical for system design purposes.

The extremes of solar events, combined with the drive towards ever lighter and more compact space flight hardware, frequently have caused problems for instrumentation, preventing the accurate characterization of the extremes of space weather. In some cases, postanalysis allowed successful recovery of data, but in order to prepare missions towards data reliability in near-real time that feed a modeling environment, new, robust technologies have to be developed. These developments will pave the way for exploring key mechanisms and regions through which extreme space weather events arise: the radiation belts (RBSP), the reconnection regions in the Earth's magnetosphere (MMS), and the nearest neighborhood of the Sun where the solar wind forms (Solar Probe+).

Priority Investigations:

How is solar wind plasma accelerated?

What is the fundamental nature of the solar dynamo and how does it produce the solar cycle?

What are the roles of mass and energy flows in the behavior of planetary magnetospheres?

What is responsible for the dramatic variability in many of the state variables describing the ITM region?

Decadal Survey Challenges:

Challenge 2: Understanding heliospheric structure, the distribution of magnetic fields and matter throughout the solar system, and the interaction of the solar atmosphere with the local interstellar medium.

Challenge 5: Developing a near-real-time predictive capability for understanding and quantifying the impact on human activities of dynamical processes at the Sun, in the interplanetary medium, and in Earth's magnetosphere and ionosphere.



Safeguard the Journey:

Develop the capability to predict the origin, onset, and level of solar activity in order to identify potentially hazardous space weather events and safe intervals

Priority Investigations:

What are the fundamental physical processes and topologies of magnetic reconnection?

How do planetary dynamos function and why do they vary so widely across the solar system?

What is the composition of matter fundamental to the formation of habitable planets and life?

Decadal Survey Challenges:

Challenge 1: Understanding the structure and dynamics of the Sun's interior, the generation of solar magnetic fields, the origin of the solar cycle, the causes of solar activity, and the structure and dynamics of the corona.

Challenge 5: Developing a near-real-time predictive capability for understanding and quantifying the impact on human activities of dynamical processes at the Sun, in the interplanetary medium, and in Earth's magnetosphere and ionosphere.

Dramatic and rapid changes in space weather that can affect humans and technology anywhere in the inner heliosphere are associated with solar particle events. Recent space weather research has shown that in a worst-case scenario (J1), unprotected astronauts that are suddenly exposed to solar particle radiation in space can reach their permissible exposure limits within hours of an event. Such events are a direct effect of the rapid release of stored magnetic energy at active regions on the Sun.

Predicting accurately when safe intervals will occur, or the exact times of sudden releases of radiation at the Sun, poses major challenges to the system science of Heliophysics. The time scales involved span several orders of magnitude: minutes and hours are associated with high-energy particle propagation from the Sun to the Earth; days are associated with arrival of a solar wind plasma, and months to years for the full development of solar explosive events.

The largest potential impact on exploration would derive from predicting "all clear" periods. This capability could improve safety by optimized scheduling of manned launches and extravehicular activities (EVAs). In recent years, several observational tools and methods have been developed and are currently being validated that would greatly improve forecasting. Early successes are (1) the capability that is now in place to image active regions on the back side of the Sun with helioseismology, to be vastly improved with the expected launch of the Solar Dynamics Observatory (SDO) and (2) the nowcasting of light-speed particles from prompt particle events that can give up to 1 hour warning of hazardous SEP arrival, and (3) STEREO heliospheric imaging that can give 1–2 days warning of the arrival of energetic storm particles and magnetic disturbances at distances where human and robotic explorers might venture. These advancements could exceed by more than tenfold previous warnings that relied on spacecraft at the L1 Lagrangian point, 1 million miles sunward from Earth.

Successful forecasting of space weather depends on (a) complete identification and observational coverage in real-time of critical solar disturbance parameters; (b) the development of observational tools, improved instrumentation that is alert and fully functional even in the midst of severe space weather; and (c) the advances in physical understanding (F and H) as a basis for theoretical and computational modeling of the Sun-Earth-Inner-Heliosphere system. These are all necessary conditions for a Heliophysics science enterprise that would fulfill its responsibility for NASA embarking on next-generation exploration activities.



Safeguard the Journey:

Develop the capability to predict the propagation and evolution of solar disturbances to enable safe travel for human and robotic explorers

Mission success of a lunar landing depends on the productivity of astronauts deploying instrumentation and collecting scientific samples in the surroundings of their landing sites. Solar activity can severely disrupt science activities for a period equivalent to short mission duration, in particular, in scenarios in which the evolution of the solar event is not sufficiently predictable.

The effectiveness and duration of space weather events on humans and technology in space critically depends not only on intensity of the solar event but also on the site of interest in the solar system and other properties of the outburst. CMEs, for example, propagate away from the slowly rotating Sun on a near-radial trajectory. Thus, whether or not the disturbance interacts with the Earth-Moon system depends mostly on the direction and width of the expanding CME.

The radiation environment in the heliosphere depends on the propagation and transport of the particles in the solar wind and on the radial evolution of, and interaction with, solar disturbances. The behaviors are complex. Some solar particle events can increase radiation intensity to critical levels very rapidly, others rather slowly or not at all. At times, even two maxima can be reached originating from a single solar event, and in extreme events, the particles tend to fill the inner heliosphere.

Heliophysics has recently made progress to better characterize the extent of solar particle events through observations from distributed vantage points. However, the observational basis for these studies needs to be improved. Despite the importance of remote sensing, the regions of the outer corona that provide the interface between the inner corona and the heliosphere (solar wind) can only be fully understood with direct in situ measurements. The Solar Orbiter and Solar Probe+ missions now in formulation will provide critically needed data from the inner heliosphere.

GCRs are modulated globally over the solar cycle but also locally through propagating transient disturbances. The outer heliosphere is thought to shield us from much of the nearly continuous GCR flux, perhaps by as much as 90% at 100 MeV/nucleon, although recent observations by the Voyager spacecraft show that the barrier, if it exists, is not in the inner part of the heliosheath. The sensitivity of the GCR flux to approaching solar disturbances has provided a valuable tool for predicting space weather hazards for spacecraft.

Priority Investigations:

How is solar wind plasma accelerated?

How do solar wind disturbances propagate and evolve through the solar system?

How do the heliosphere and the interstellar medium interact?

Decadal Survey Challenge:

Challenge 2: Understanding heliospheric structure, the distribution of magnetic fields and matter throughout the solar system, and the interaction of the solar atmosphere with the local interstellar medium.

Challenge 5: Developing a near-real-time predictive capability for understanding and quantifying the impact on human activities of dynamical processes at the Sun, in the interplanetary medium, and in Earth's magnetosphere and ionosphere.



Safeguard the Journey:

Understand and characterize the space weather effects on and within planetary environments to minimize risk in exploration activities

Priority Investigations:

How do coupled middle and upper atmospheres respond to external drivers and to each other?

What is responsible for the dramatic variability in many of the state variables describing the ITM region?

Decadal Survey Challenges:

Challenge 3: Understanding the space environments of Earth and other solar system bodies and their dynamical response to external and internal influences.

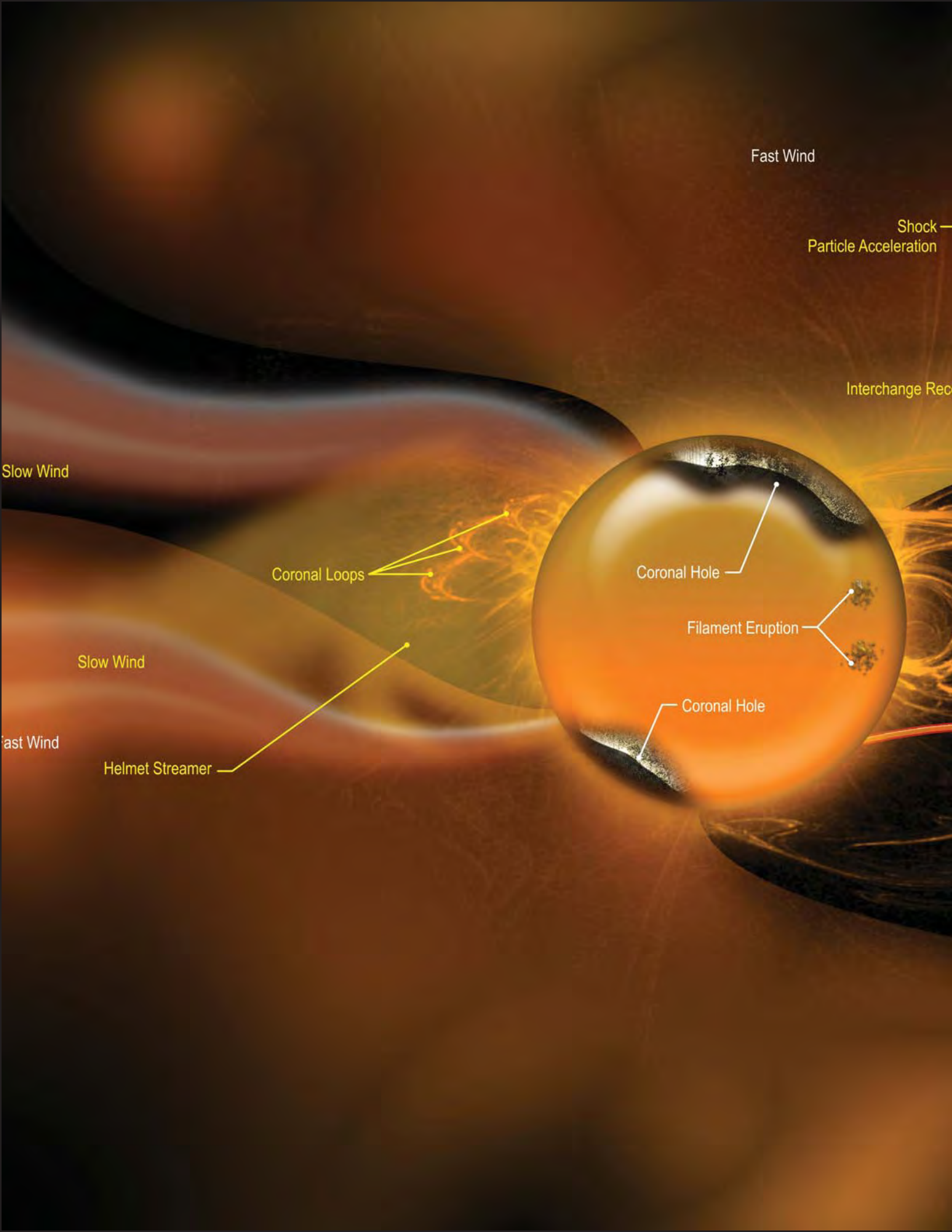
Challenge 5: Developing a near-real-time predictive capability for understanding and quantifying the impact on human activities of dynamical processes at the Sun, in the interplanetary medium, and in Earth's magnetosphere and ionosphere.

Exploration activities are inherently risky. Beyond the technical challenges, human and robotic explorers across the solar system will be affected by the planetary plasma environments that respond to solar- and heliosphere-driven space weather. The “near-planet” radiation environment, applicable to Earth and all other planetary systems, is of particular concern for exploration activities as this is where exploration will take place for extended periods of time. Space weather at planets can intensify and restructure radiation belts. An effective strategy that minimizes cumulative dose from this hazard in particular includes avoidance through advance warning. The key role that Heliophysics occupies is to develop understanding of the physical processes that create and drive the radiation environments near planetary bodies. In the meantime, improved characterization of these environments and identification of parameters that indicate changes will reduce risk to exploration activities to the extent possible.

The ionosphere, thermosphere, and mesosphere enable exploration activities in those planetary environments. These layers of the planet's atmospheres provide a means for long-range communication through ionospheric reflection of radio signals. However, surface-to-orbit and surface-to-surface communications are sensitive to Heliophysical processes. Aerobraking is a novel technique that utilizes the thermosphere and mesosphere instead of costly propellant. Spacecraft control in low orbits and in aerobraking parking orbits depend on the knowledge of upper atmosphere neutral density. Neutral density variability at aerobraking altitudes is partially controlled by dynamical influences from the planetary atmosphere.

Lunar dust interacts with the solar radiation and wind output. The plasma and UV radiation environment at the Moon's surface contributes to recognized problems with lunar dust. Dust grain adhesion on astronaut suits and instrumentation is not fully understood or resolved.

Heliophysics science reduces risk for exploration by directly addressing the issues mentioned above. The Radiation Belt Storm Probes (RBSP) mission in development will measure the variability of the Earth's radiation belts; ionosphere/thermosphere/mesosphere missions, including AIM and Coupled Ion Neutral Dynamic Investigation (CINDI) in operation, will investigate the effects of space weather on the outer atmosphere of the Earth and at Mars; and the Artemis mission will utilize two spacecraft to investigate the solar wind and dust interaction near the Moon. Heliophysics, as an interdisciplinary science, will potentially benefit from planetary exploration as planets and the moon hold unique archival clues on the distant past of solar terrestrial processes that will allow us to understand the system in more depth and detail.



Fast Wind

Shock
Particle Acceleration

Interchange Rec

Slow Wind

Coronal Loops

Coronal Hole

Filament Eruption

Coronal Hole

Slow Wind

Fast Wind

Helmet Streamer

This image under construction

Chapter 2

STATE OF THE DISCIPLINE

The Heliophysics discipline has been highly productive and successful in meeting the science goals established for the Heliophysics Division at NASA. Roadmaps have been key elements in continuing the productivity of the discipline. Strength from continuity of purpose derives from building the new strategy on the foundation of previous roadmaps, taking into account new scientific discoveries and reassessing the landscape of the discipline. These are the starting points for building this roadmap that lays out a prioritized set of science objectives for future Heliophysics missions. Consideration of the integrated support of all program elements led to a launch queue for the highest priority science Targets as described in Chapter 3.

Connection

Current
Sheet

Fast Wind

Suprathermal Ions

CME

Investment Returns 2006–2009: Recent Discoveries Pose Challenges for a New Era in Heliophysics

Scientific research leads to new insights, increased understanding, and eventually to predictive capabilities and useful applications. The Roadmap Team assessed progress in Heliophysics research to build upon advances made since the 2003–2013 Decadal Survey of Solar and Space Physics. The team identified several developments over the past few years that have led to new directions and posed new challenges for our science discipline.

Since the publication of the Decadal Survey, our network of Heliophysics spacecraft has both gained and lost observational capabilities. The gains enable new science topics to be addressed and the losses potentially leave gaps in our ability to make further progress for other topics.

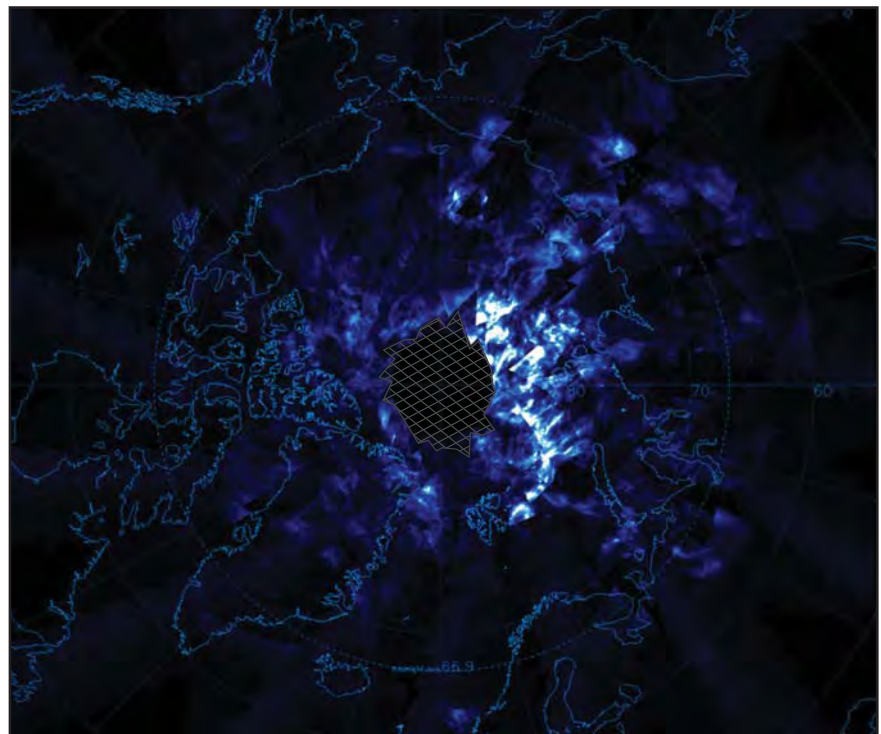
We have seen the launch of missions covering a broad scientific range, from the origins of noctilucent clouds in the upper atmosphere (AIM), the origins of substorms (THEMIS), the three-dimensional structure of the magnetosphere (TWINS), the three-dimensional structure of the corona and interplanetary space (STEREO), and the fine-scale structure of the solar surface (Hinode). This launch rate was made possible by making extensive use of smaller Principal Investigator (PI)-led Explorer missions, missions of opportunities, and foreign partnerships. Similar arrangements will be important for maintaining an adequate rate of further progress.

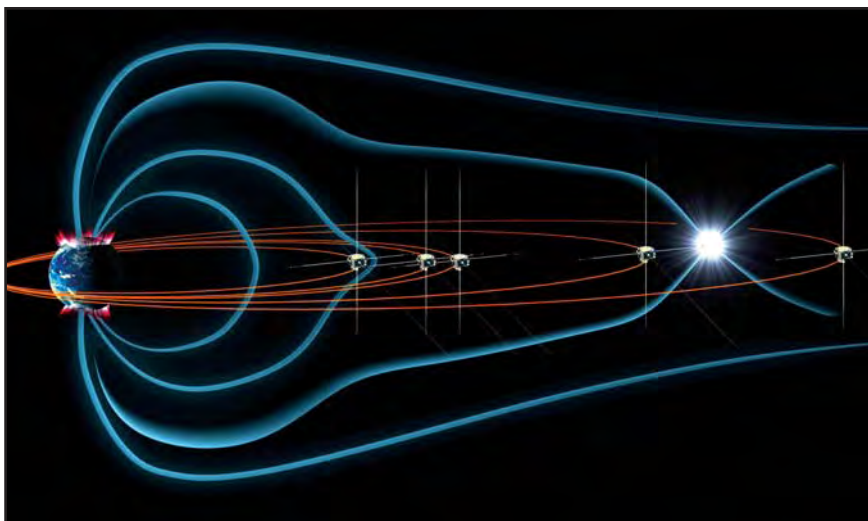
During this same period, the Team took note of the loss of observational capability attendant to the loss of several observational platforms, including IMP-8, IMAGE, Polar, and Ulysses and critical instrumentation on the TIMED and FAST missions.

We reviewed the scientific literature and the assessments of the Senior Review panels. Scientific results were identified and mapped to the Research Focus Areas. Initial results were presented at the Roadmap Community meeting and further input was solicited. The study produced several highlights. First, magnetic reconnection and particle acceleration remain the dominant fundamental research topics in our field. The last few years have brought direct observations of reconnection occurring within the magnetosphere, the solar corona and, surprisingly, in the solar wind. Reconnection research is ready to transition from an exploration and discovery phase into detailed understanding of the mechanisms that trigger and moderate it. Our second observation is that the primary breakthrough area for solar terrestrial “cause-and-effect” science is at the boundaries or interfaces between regions. For example, recent observations with the CINDI instrument on the C/NOFS spacecraft have revealed an unexpected drop in density of the ionosphere, effectively lowering Earth’s boundary with space, as a result of the long and minimal activity on the Sun during the past solar minimum.

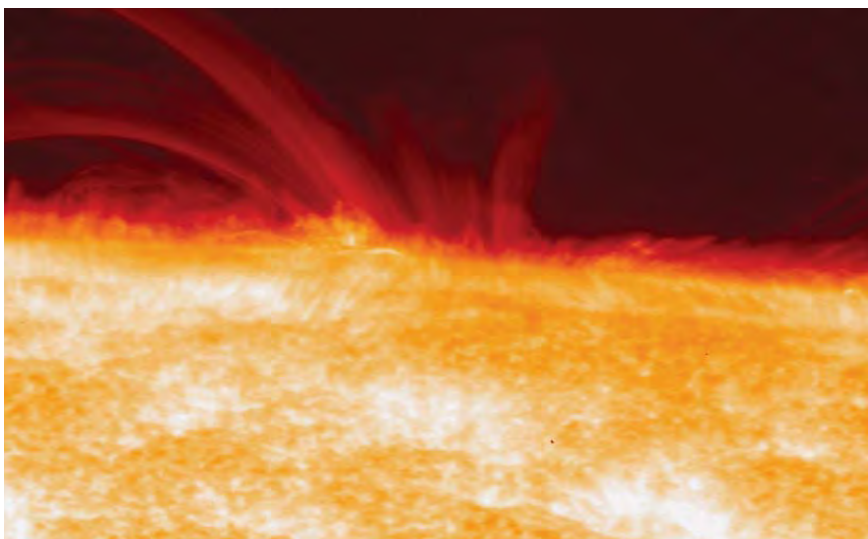
Following are additional noteworthy examples.

The AIM spacecraft conducted the first-ever survey of noctilucent clouds and has discovered that the clouds are far more strongly coupled to the lower atmosphere than had been previously believed; exploration of this connection is just beginning. The image below reveals Northern Hemisphere noctilucent clouds forming a so-far-unknown arctic oval pattern. It is known that at the altitude of 50 miles above the Earth's surface, the quasi-constant influence of solar irradiance on Earth's weather system diminishes. The AIM data show that the upper atmosphere is interacting with the much more variable influence of short-wavelength solar emission that was thought to act mostly on plasma. Here, the potential impacts of human influence on climate and solar influences reaching further down into the atmosphere can be assessed and compared.



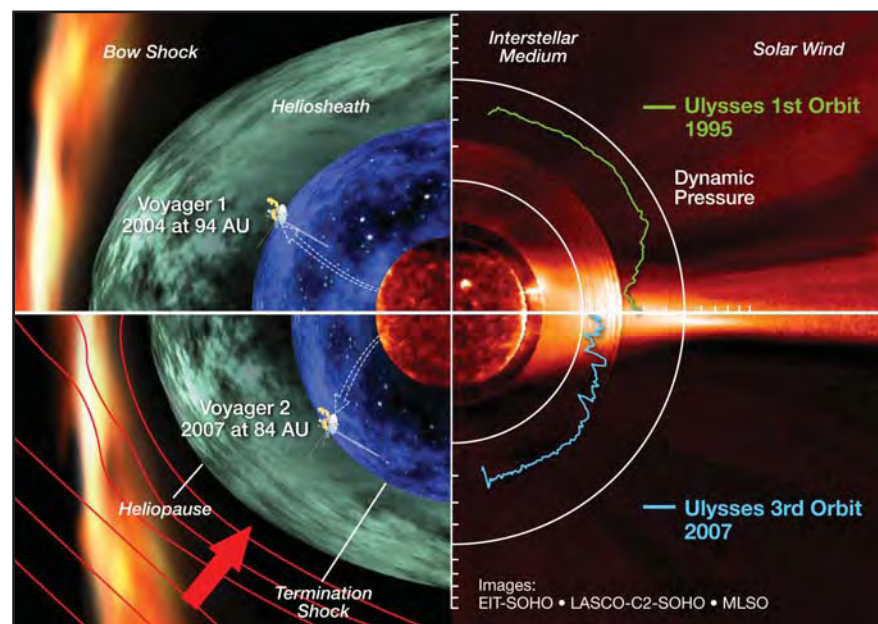


Using the five THEMIS satellites, researchers discovered that explosions of magnetic energy a third of the way to the Moon power the substorms that cause sudden brightening and rapid movements of the auroras. Scientists found the cause to be magnetic reconnection and confirmed that magnetic reconnection triggers the onset of substorms. A long-standing challenge remains to understand the energy and mass transfer between the highly coupled magnetosphere and the ionosphere. Two of the THEMIS spacecraft will soon be redirected into lunar orbit to examine plasma processes occurring in the interaction of the solar wind with the Moon. This exploration of the lunar plasma environment will offer insight into the universal processes occurring in the interaction of plasma with rocky bodies, but will be of significant benefit to design and implementation of the human and robotic activities at the Moon.



The Hinode spacecraft's high-spatial resolution observations of the Sun have had an impact on solar physics comparable to the Hubble Space Telescope's impact on astronomy. Researchers are analyzing the plethora of new information on the magnetic carpet—the upward transfer of magnetic energy from the Sun's surface toward the corona above. These observations give rise to a variety of processes ranging from the quiet-time solar wind to the most intense solar eruptions that can endanger astronauts and robotic explorers in space. The STEREO spacecraft continue on their paths away from the Earth in leading and trailing orbits, tracking

magnetic disturbances (CMEs) from Sun to Earth. On February 6, 2011, they will provide our first-ever observation of the full solar disk, which will enable scientists and forecasters to track large sunspot groups over their entire lifecycle.



The Ulysses mission has found that the current solar magnetic field strength in the heliosphere is about 40% lower than during any solar cycle since the space age began. Simultaneous measurements by the SOHO spacecraft indicate that the Sun's polar fields are smaller by a factor of 2. The change in strength suggests that the upcoming solar cycle may be significantly different from what we have observed in the past. The heliosphere as a whole may temporarily shrink in size and, therefore, the intensity of components of GCRs at Earth may rise to record levels. In this new environment, the recently launched IBEX mission will image, for the first time, the dynamic heliospheric interaction with the local interstellar medium via neutral atoms. At the same time, the two Voyager spacecraft, the most distant man-made outposts experience this region. Their eventual encounter with the heliopause, the effective boundary of the Sun's influence, may occur within a few years if the solar wind continues to decrease.

Heliophysics Landscape–SWOT Analysis

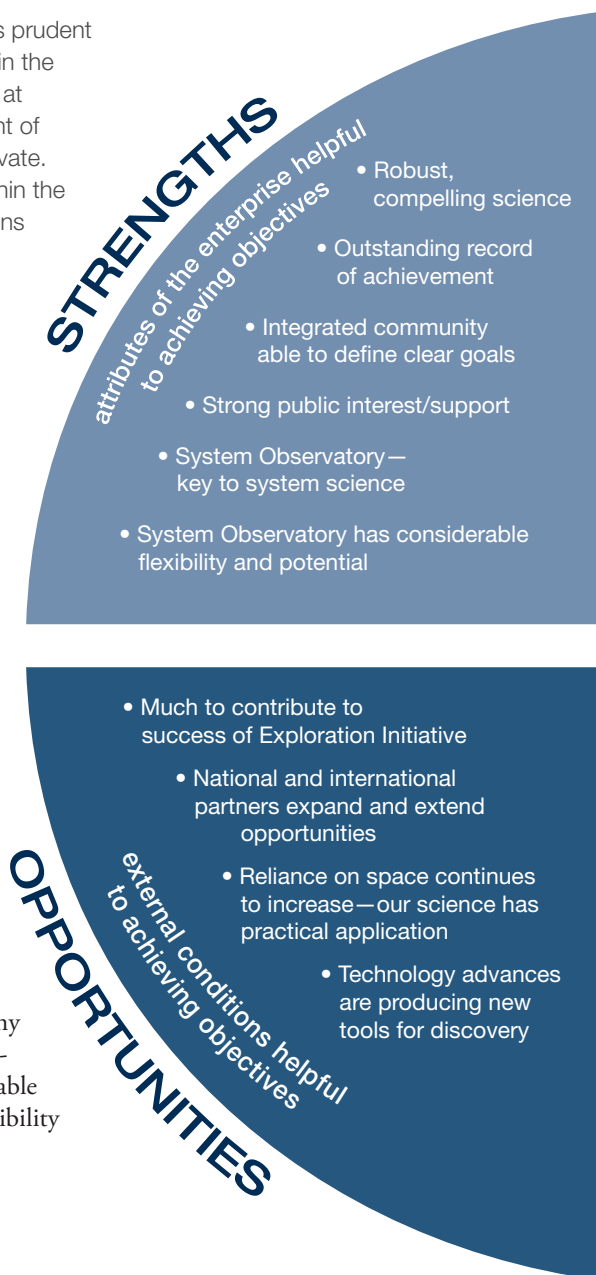
In assessing the future direction of Heliophysics research as a discipline, it is prudent to candidly consider the strengths, weaknesses, opportunities, and threats in the Heliophysics landscape. The concept of a “SWOT” analysis was developed at Stanford University in the 1960s and has proven to be a valuable component of strategic planning across a wide range of organizations, both public and private. For this analysis, we considered internal attributes to be those that exist within the Heliophysics Division and/or heliophysics community while external conditions are those that exist outside or beyond (but may be internal to NASA as an Agency). The intent was to provide a context for formulating the strategies, implementations, and decisions reached through this roadmapping effort.

With this analysis, we found the Heliophysics Division to be healthy, vibrant, and becoming more integrated with the efforts of other agencies than ever before. Significant weaknesses and threats to the enterprise do exist and must not be ignored for successful execution of this science strategy but, if the enterprise (including NASA, the science community, and decision makers) is willing to take bold steps and determinedly exploit its strengths, then great opportunities for science and for society are within reach.

Strengths

A primary strength is that Heliophysics has a portfolio of robust and compelling science. The science is broad and, at the same time, sufficiently deep to produce new discoveries and foster fundamental scientific understanding of our home in space and the interconnected physical processes that link the Sun to the Earth and planets to the edges of the solar system. Along with a rich diversity of ideas, Heliophysics benefits from a community that is more integrated than ever before and is therefore better able to define clear strategy and priorities across the discipline. This complements the fact that there is strong public interest in and support of the science of Heliophysics. Both the community integration and public awareness are outcomes of concerted efforts over many years. A similar, but more tangible, strength is the concept of the Heliophysics System Observatory—combinations of missions that, taken together, enable larger scale investigations. This distributed observatory has considerable flexibility and grows in capability with each new mission launched.

Objectives within the strategic plan were evaluated within the context of the SWOT to determine the achievability of each objective and how it might best be approached.



WEAKNESSES

attributes of the enterprise that are barriers to achieving objectives

- System Observatory is serendipitous—not planned for maximum effectiveness
- Inability to perform simultaneous observation of key parts of the system
- Diminishing opportunities for new employee training
- “Succeed at any cost” implementation philosophy
- Implementation of risk posture can increase cost
- Significant mission cost increases from planning to implementation

Weaknesses

While the existence and flexibility of the Heliophysics System Observatory is a primary strength, a weakness is that its collective capability is serendipitous, not planned, and somewhat fragile due to the aging of the satellite fleet. Long-term or continuous observations of key parts of the system are particularly hard to maintain. The rising cost of individual missions has reduced the number of investigations that can be accomplished within budget resources. Mission costs have been strongly influenced by external factors but also reflect some internal weaknesses related to, for example, disconnects between planning, procurement, and implementation methods. Diminished launch frequency is an example of a weakness with long-term consequences through diminished opportunities to retain experienced personnel in flight hardware development and the inability to attract fresh talent to the field. The identified weaknesses represent opportunities for growth and improvement.

Opportunities

Heliophysics has much to contribute to other parts of the NASA enterprise. The science is basic to understanding many questions of the origin and evolution of the universe. Understanding and ultimate prediction of the space environment is important to reduce risk and improve productivity both within and outside of NASA. The expanding importance of the discipline provides opportunities to both educate the public and to meet the challenges of understanding the Heliophysics system. Technological advances in information sharing, space instrumentation, propulsion, communications, and other areas are producing new tools that will enable discoveries at a rapid pace. At the same time, the increasing reliability of society on those technologies operating in space creates an urgency for the knowledge generated by the Heliophysics program. Thus, there is a need for expanded and extended Heliophysics partnerships with other agencies in the U.S. space enterprise (DoD, DOC, DOE, NSF, etc.).

THREATS

external conditions adversely affecting performance

- Launch opportunities at risk
- Flat budgets while cost of doing business increases
- Public opinion requires that all missions be successful
- Future priorities for NASA as an agency are uncertain
- Escalation of the “cost of doing business”

Threats

Threats that lie outside of the direct influence of the Heliophysics program must still inform a rational strategy for the future. It is well known that recent elimination of the Delta II launcher has placed severe constraints on new missions, limiting them to smaller scientific payloads or requiring the use of much more expensive Evolved Expendable Launch Vehicle (EELV) vehicles. Funding projections are flat even while new demands are being placed on the federal budget. Shortfall in the training of future engineers and scientists has the potential to lead to long-term disruptions to the vitality of science and the U.S. space capability. Within this environment, we have recommended scientific priorities to make fundamental contributions worthy of public investment.

Inferences Drawn From SWOT Analysis

The SWOT analysis provided valuable guidance for the development of this strategic plan. The text to the right summarizes the dominant issues raised by the analysis, identifies the NASA Heliophysics Division processes and structures affected, and then lists the solutions recommended in this roadmap. We intend to provide a future direction for Heliophysics science at NASA that is based on a clear assessment of current challenges and constraints.

The Earth and the planets are embedded in a constantly changing medium powered by the Sun. The scale sizes are vast. Ideally, we need to simultaneously observe activity on the Sun, the properties of the solar wind as it flows through the solar system, the three-dimensional configurations of the planetary environments as they react, and the properties of the heliospheric boundary layers. It is clear that in the coming years, heliophysics will be challenged to maintain and even expand the breadth of its system-level observatory to meet the needs of our space-faring Nation. Other key challenges to the research program include instability in the budget, the growth in cost of missions and the uncertain availability of Delta-class launch vehicles that have been the workhorse launchers for the Heliophysics Division.

The premises of the roadmap have been conceived to address these challenges. Key among them is the development of a list of prioritized science Targets that embody the science objectives of future missions. The science priorities were identified through a community-based process informed by recommendations of the NRC, by Agency objectives, and other related needs of the Nation (See Appendix A for details). Important considerations were recent Heliophysics accomplishments and expectations regarding the scientific contributions of missions under development. With a focus on science objectives rather than specific mission point designs, a flight mission implementation strategy was formulated with the flexibility needed to deal with new discoveries, budget changes, the availability or loss of launch options, and the potential for new partnership opportunities. It is anticipated that this approach will facilitate innovation and mitigate some areas of past cost growth.

It was determined that the HSO is a predominant asset and provides an outstanding capability for continued discovery. Significant synergy is manifested in adding missions to the existing portfolio of the HSO. This is possible with frequent launches allowing investigation of Heliophysics as a system of cause-and-effect relationships within the Sun-heliosphere-planetary system and the potential for simultaneous observing from distributed, strategic viewpoints. A technology development program is recommended that is focused on enabling and enhancing the high-priority science Target-derived missions.

Finally, it is recommended that data from these multiple sources be synthesized through analysis, modeling, and theory to develop the deep scientific understanding and practical knowledge urgently needed by our increasingly technical society.

**Summary SWOT Results:**

- Progress across the system requires a broad-based approach with frequent launches
- Launcher availability crisis requires flexible implementation approach
- Budget uncertainties require flexible implementation approach
- Strategies are required for mission cost containment

Derived Challenges:

- Identification of vital and urgent science problems
- Launch cadence versus mission capabilities versus budget realities
- Flexible flight mission strategy to yield:
 - New discoveries across the system
 - Effective integration of technologies, theory, modeling, and data analysis
 - Efficient budget management
 - Compatibility with changing launch market
 - Mission cost containment
- Legacy planning-procurement-implementation processes

Roadmap Solutions:

- Analysis of Decadal Survey Science Challenges as a function of progress and future capabilities
- Prioritized science queue rather than a mission queue
- Mission objectives enable fundamental and system science
- Compete mission architectures at formulation phase
 - Mission LCC targets
 - Greater launch frequency in both LWS and STP mission lines
- Heliophysics System Observatory leverage science progress
- Coordinated objectives for supporting R&A structures
- Processes to “procure what you plan” and “implement what you procure”

New Approach for Heliophysics Mission Planning and Implementation

Based on the lessons learned from the SWOT analyses, this roadmap presents a new approach for heliophysics strategic mission planning and implementation. With a focus on science rather than mission point designs, a strategy is presented with the flexibility needed to deal with new discoveries, budget fluctuations, the availability or loss of launch options, and the potential for new partnership opportunities. It is anticipated this approach will facilitate innovation and mitigate some areas of past cost growth.

The roadmap recommends a set of six new mission priorities along with a launch sequence, cadence, and mission size category. Science objectives, scope, requirements, and mission size categories are given. Neither specific mission architectures, point designs, nor implementation approaches are described. The roadmap recommends a competitive mission design process be initiated when NASA is ready to proceed with the next mission in the queue.

Via existing SMD Announcement of Opportunity (AO) processes, each science investigation proposal would be led by a principal investigator (PI) who is typically affiliated with a university, research institution, or government laboratory. The PI selects team members to develop the investigation and define the mission design concept and requirements. The team brings together the skills and expertise needed to develop the investigation and define the mission from design concept, to the data analysis, and to the application of that data for scientific progress. Specifics on project management (center-led or PI-mode), and acquisition of the spacecraft bus, launcher, and specific technologies are determined on a project-by-project basis and specified in the AO as constraints to mission design. Proposals will require careful trade-offs between science and cost to produce investigations with the highest possible value for the cost cap specified.

While this approach may be new to the Heliophysics Division, the model has been used successfully by NASA within other programs. For example, in the New Frontiers Program, the missions tackle specific solar system exploration goals identified as top priorities by consensus of the planetary community. The program solicits proposals for an entire mission, led by a PI that develops the scientific objectives, instrument payload, and mission design. There is a cost cap specified. The first set of New Frontier priorities were determined by the Planetary Division's decadal survey, conducted by the Space Studies Board of the National Research Council at NASA's request.

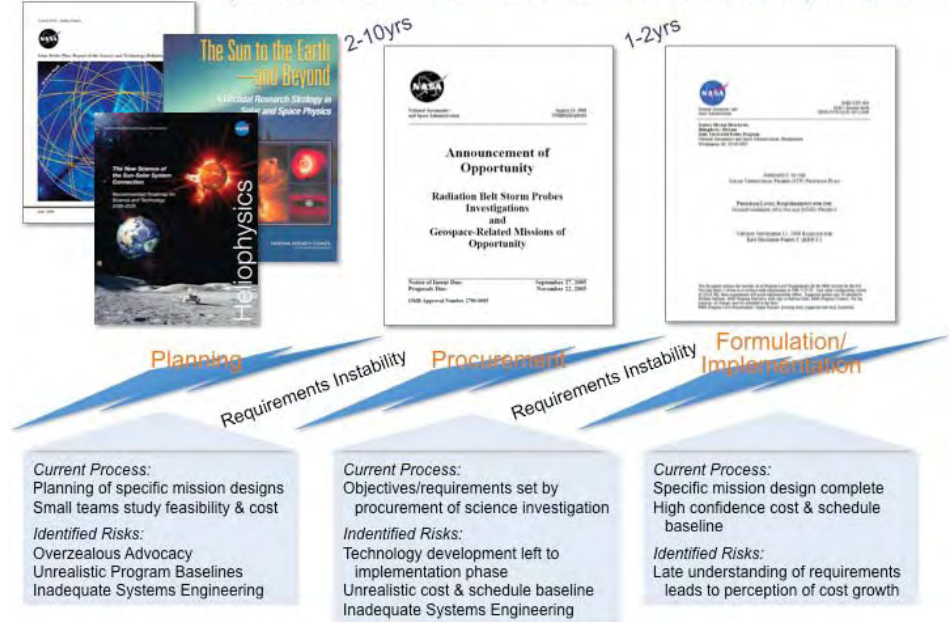
The approach set forth by this roadmap is similar in that mission objectives and scope are determined by community-based strategic planning, the investigations and mission design are to be competed via an AO, and there is emphasis on cost containment. The approach differs in that specific science targets are identified for each mission rather than a range of equally important topics.

The heliophysics community is committed to the principles of open competition and merit review as a key to excellence. The roadmap team believes this new approach has the potential to contribute to the containment of total mission cost and development time while improving performance through extensive competitive peer review, validated technologies, and control of design requirements while maintaining a strong commitment to scientific excellence.

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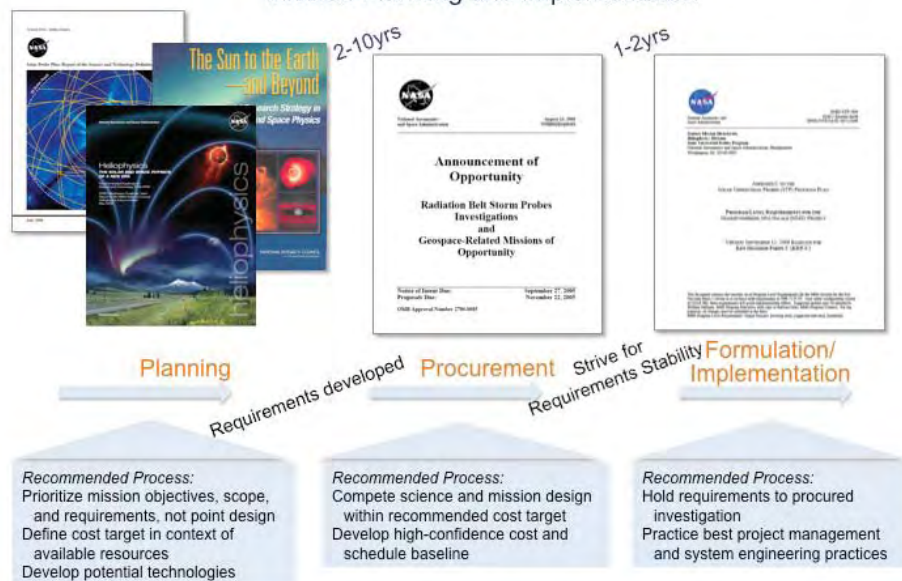
Decadal Surveys and their associated implementation roadmaps are intended to be strategic planning documents. Mission point designs and acquisition specifics go well beyond strategy and into tactics. These tactics have proven to be unrealistic as the underlying resource, mission risk, and launcher assumptions changed over the course of the decade.

SWOT analyses indicate that current planning/procurement processes can create unrealistic cost/schedule expectations



The major strength of the new plan is in leaving the definition of specific mission design to thoughtful analysis from the community through peer review within the context of the resources and technologies available at the time of mission formulation and implementation.

This Roadmap Recommends a New Approach to Mission Planning and Implementation

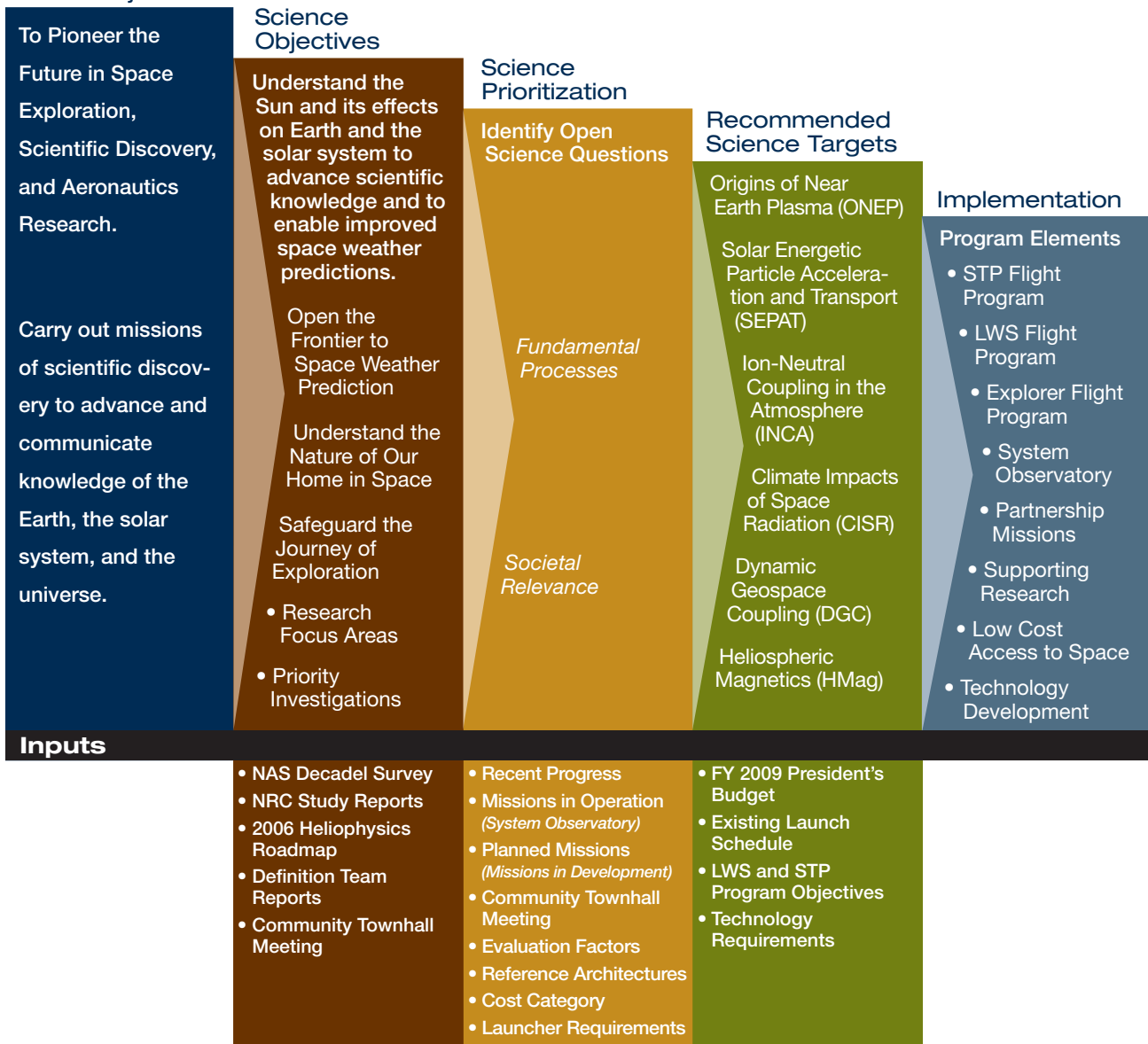


Logical Framework for the Roadmap

The roadmap is built on a logical framework that begins with U.S. National and NASA objectives and follows a series of more and more detailed steps, resulting in a launch queue populated by priority science Targets.

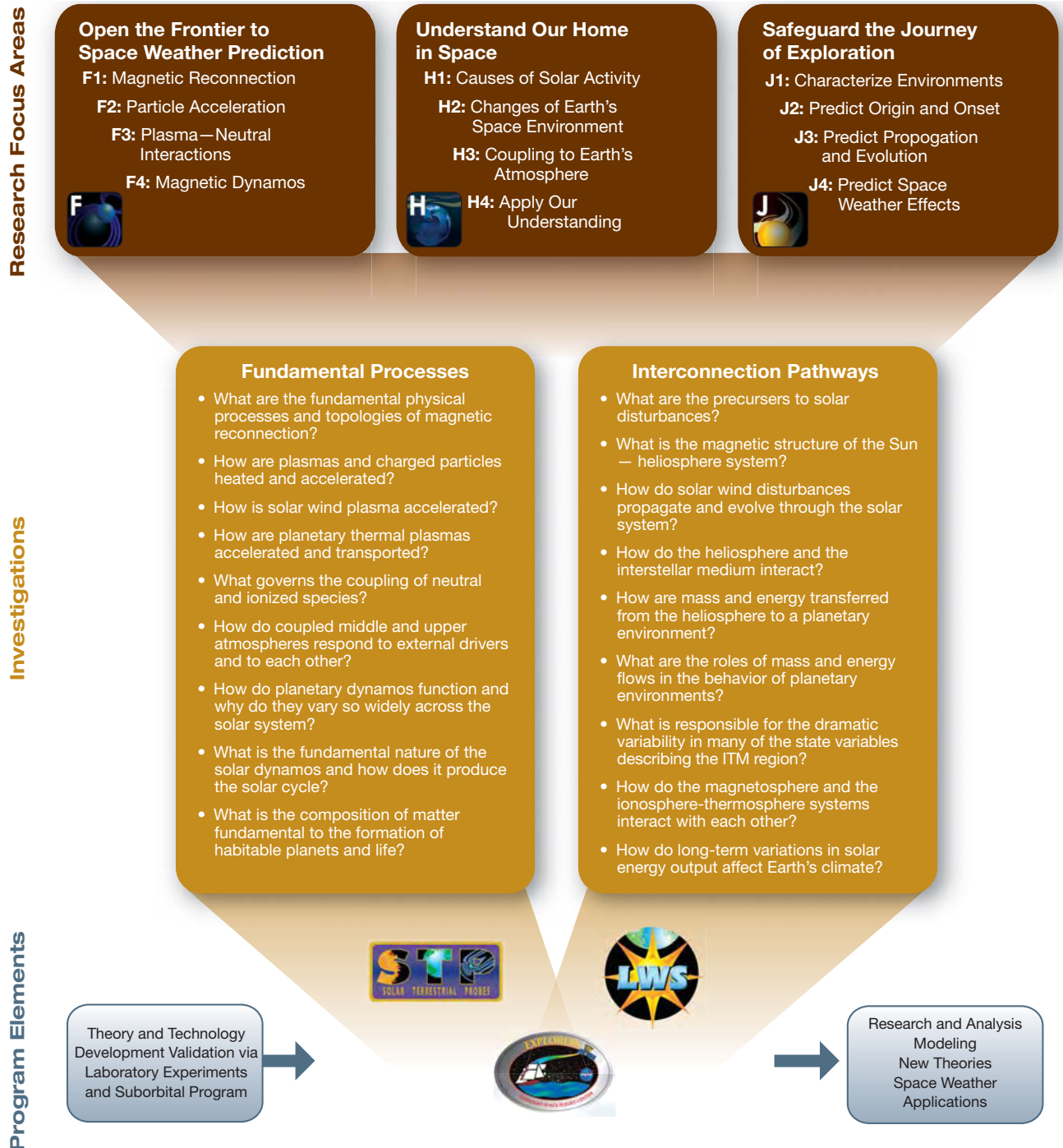
The Science objectives described in Chapter 1 flow through the RFA and Priority Investigations to a prioritization process as shown in the graphic on this page and detailed on the facing page. Analysis of past and recent progress resulted in a comprehensive list of Open Science Questions (OSQs) associated with each of the 18 investigations. These were prioritized following the scheme described in appendix A. These OSQs became the basic science objectives for future missions and are called science Targets to indicate that the science is focused and they are not missions in the usual sense of the word. Measurement techniques and architectures have not been specified. The six highest priority Targets were assigned to either the STP or LWS mission lines, depending on the science content of the investigation. Successful implementation of missions based on the science Targets will be through an implementation process that involves all programs in the Heliophysics Division acting in concert.

U.S. National & NASA Objectives



Science Flow From Objectives to Implementation

The Heliophysics Division science objectives are parsed into three general areas: F (Frontier), H (Home), and J (Journey). Four Research Focus Areas comprise each as discussed in Chapter 1. From these flow a set of Investigations. These Investigations do not map one to one with the Research Focus Areas, but are derived from the RFAs and the 2003 Decadal Survey Challenges. The Investigations are further divided into two groups, those appropriate for funding through the STP mission line addressing fundamental processes, and the LWS mission line addressing science of societal relevance. The science objectives for each of the science Targets can thus be traced backward to higher level science objectives. The science objectives will provide guidance to proposers in the Explorer Program as well.





A stylized, artistic illustration of a blue flower or nebula-like structure. The center features a small globe of the Earth, with swirling blue and white patterns radiating outwards, resembling petals or solar wind. The background is a dark space filled with numerous small, bright stars. The overall color palette is dominated by various shades of blue and teal, with white highlights on the flower's 'petals' and the stars in the background.

Chapter 3

THE HELIOPHYSICS PROGRAM ELEMENTS

A program that achieves the science objectives of the Heliophysics Division requires a strategy that leverages all the program elements of the Heliophysics Division. These include the explicitly budgeted STP, LWS and Explorer mission lines and the Heliophysics System Observatory funded through the Supporting Research and Technology program. For each of these elements we discuss how existing missions, missions in development and new science targets are/will address the open science questions flowing from the science goals of the RFAs, and Investigations described in Chapter 2 and Appendix A. Each program element has a critical role in implementing the science-based launch queue strategy, the basis of this Roadmap.

The Heliophysics Program Elements

The Heliophysics Program Elements are the Solar Terrestrial Probes, Living with a Star and Explorer flight missions lines and six Supporting Research and Technology Programs. They are all critical to the development and unified scientific understanding of the Heliophysics System. Partnerships with other national and international agencies and within NASA provide important opportunities to meet shared science goals to the benefit of the nation.

This chapter describes the Program Elements and their relationship to the science goals and objectives of Heliophysics reviewed in Chapters 1 and 2 and how they will work together to implement the new science strategy in this Roadmap. The state of the discipline and the process for developing the Open Science Questions and their prioritization was described in Chapter 2. This chapter defines each of the programs and shows how the open science questions are being addressed. The description begins with a review of the currently operating missions, missions in development and new strategic science targets in the STP and LWS strategic mission lines and relevant aspects of the Explorer mission line. Their relationship to the science flowdown is a key element in the logical framework of the Roadmap. The chapter also reviews the Supporting Research and Technology programs and how they support the Roadmap strategy.

We end up with a set of six new science Targets along with a launch sequence and cadence recommended for their implementation. Only science objectives are given. We neither describe specific mission architectures, point designs, nor mission implementation approaches. Rather we recommend a competitive procurement process be initiated when the Division is ready to procure the next science Target in the queue. A detailed discussion of Target science is in Chapter 4.

The Heliophysics Resources and Approach

The observational and functional resources of the Division are listed in the accompanying chart. The major observational resource, the HSO, and the functional resources are devoted to observation and study of the Heliophysics system to accomplish desired outcomes. This graphic is intended to stress the interdependence not only of the science but also the means to achieving successful scientific progress. Each of these resources will be touched upon in this chapter.

Heliophysics Research Program

<i>Program Elements</i>	<i>applied to...</i>	<i>yields...</i>
<ul style="list-style-type: none"> • STP Flight Program • LWS Flight Program • Explorer Flight Program • System Observatory • Partnership Missions • Supporting Research • Low Cost Access to Space • Technology Development 	Heliophysics System <ul style="list-style-type: none"> • Sun • Corona • Heliosphere • Magnetospheres • Ionospheres • Upper Atmospheres • Interstellar Boundary 	Outcomes <ul style="list-style-type: none"> • Understanding • System Models • Applications <ul style="list-style-type: none"> - Space Weather - Climate • Integrated Space Science • New Vision

The Flight Programs

The flight elements of the program include the STP, LWS, and Explorer missions. Missions in each of these categories include missions currently in formulation or in development that address compelling science objectives deemed to be essential for meeting the Heliophysics goals. The science objectives for each of these missions and the recommended new science Targets flow down from higher level goals and objectives.

In the study of Heliophysics, these missions trace the flow of energy, mass and momentum through regions and across boundaries within the heliosphere. Predominantly, the flow and transfer originates within the Sun's interior, crosses interplanetary space, penetrates planetary magnetospheres and finds a sink in planetary upper atmospheres, or propagates out to the edges of our solar system where it interacts with the interstellar space. To emphasize the system aspects of our discipline, we ascribe four components in a conceptual framework to this networked flow of energy, mass, and momentum. The Sun can be thought of as the source, the interplanetary space as the conduit, the magnetosphere as the regulator, and the planetary ionospheres-thermospheres as the sinks. We use this nomenclature in our graphics to indicate the scientific center of gravity of the missions realizing that there is significant overlap which we have tried to indicate by the proximity of the icons to the boundaries.

The following sections show the science flowdown for all missions, including operating missions, missions in formulations and development or planned future science Targets and their intended launch dates based on FY 2009 budget information. The color of the string in the balloon charts indicates the status of the mission. The green is used for new Targets. Other colors indicate operating and missions in development. The flowdown charts list the Priority Investigations from Chapter 2 in the first column. The second column lists the top Open Science Questions for each of the Investigations being addressed by the missions listed in column 3.

Solar Terrestrial Probes Flight Program

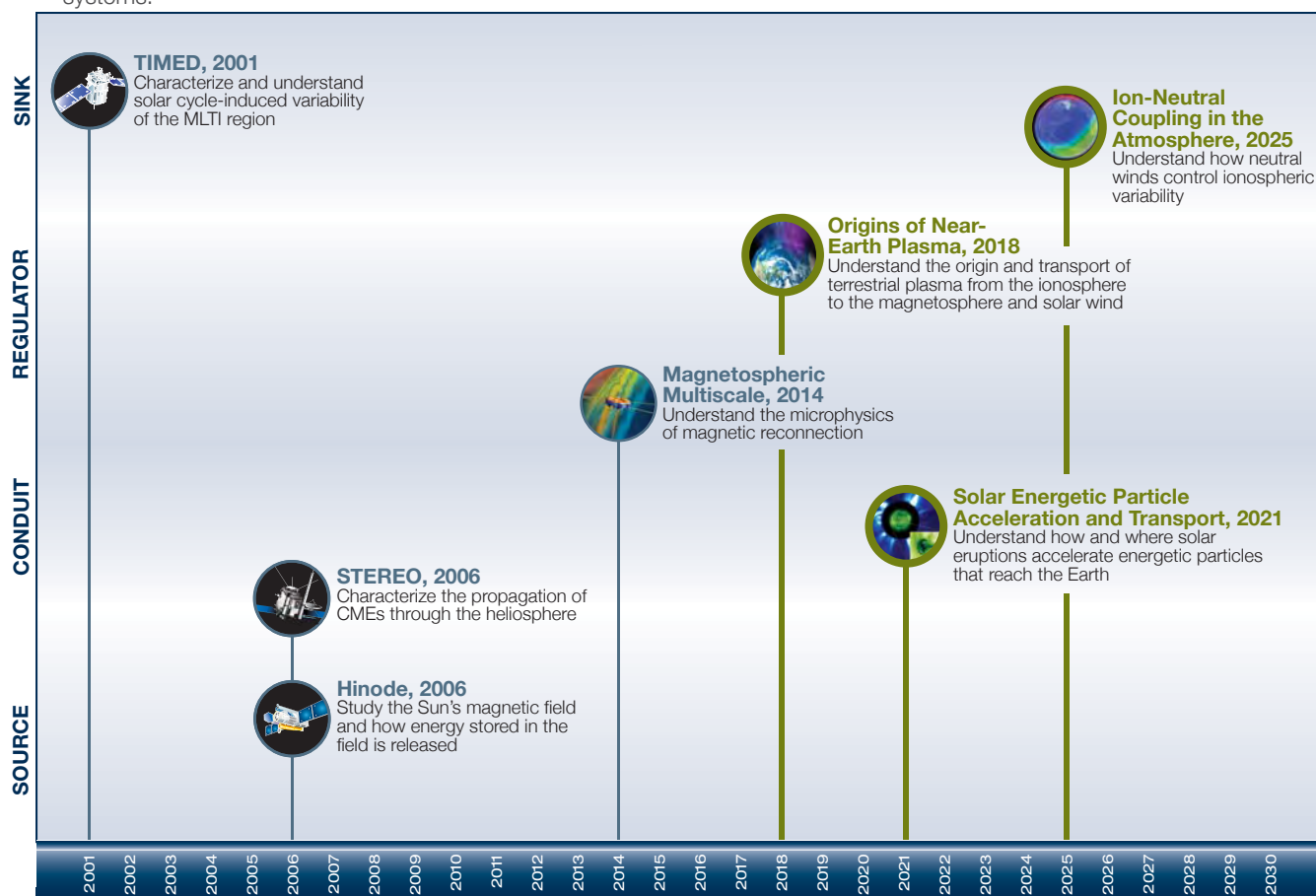


The STP program explores fundamental solar and space physics processes occurring within the solar system and how those affect the nature of our home in space.

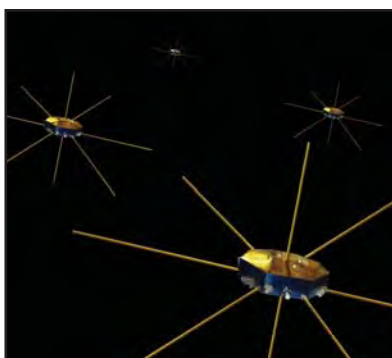
The goal of the STP program is to understand the fundamental physical processes that determine the mass, momentum, and energy flow in the solar system from the Sun, to planetary bodies including Earth, and to the interstellar boundary. The Earth and Sun are linked together to form the system that has given origin and sustenance to our lives. STP missions study this system for insight concerning how the system evolved, what will happen in the future, and this will affect us. Successive missions target the “weakest links” in the chain of understanding. The missions use a creative blend of in situ and remote sensing observations, often from multiple platforms.

The objectives of the STP program are to:

1. Understand magnetic dynamos, reconnection, heating, and particle acceleration.
2. Understand the coupling of charged and neutral particles, and
3. Understand how the dynamic nature of the electromagnetic and plasma space environment determines the nature of our home in space and other planetary systems.



Missions Currently in Development



Magnetospheric Multiscale (MMS) Mission

Understand the microphysics of magnetic reconnection.

The MMS mission will use Earth's magnetosphere as a laboratory to study the microphysics of magnetic reconnection, a fundamental plasma-physical process that converts magnetic energy into heat and the kinetic energy of charged particles. In addition to seeking to solve the mystery of the small-scale physics of the reconnection process, MMS will also investigate how the energy conversion that occurs in magnetic reconnection accelerates particles to high energies and what role plasma turbulence plays in reconnection events. These processes—magnetic reconnection, particle acceleration, turbulence—occur in all astrophysical plasma systems but can be studied in situ only in our solar system and most efficiently in Earth's magnetosphere, where they control the dynamics of the geospace environment and play an important role in the phenomena known as “space weather.” The MMS mission is comprised of four identically instrumented spacecraft that measure particles, fields, and plasmas.

Open STP Science Issues Currently Targeted

What are the fundamental physical processes and topologies of magnetic reconnection?	<i>What are the fundamental physical processes of reconnection?</i>	
	Inventory the mechanisms leading to reconnection on the Sun. Where are they located? Where are the acceleration regions?	Hinode
	<i>Understand the microphysics of magnetic reconnection by determining the kinetic processes responsible, especially how reconnection is initiated.</i>	MMS
How are plasmas and charged particles heated and accelerated?	<i>How are charged particles accelerated & decelerated?</i>	
	Determine how particles are accelerated through magnetic reconfiguration	MMS
How is the solar wind accelerated?	<i>What are the sources of energy for solar wind acceleration?</i>	
	Investigate the interaction between the Sun's magnetic field and the corona	Hinode
	<i>Where does solar wind acceleration occur?</i>	
How do coupled middle and upper atmospheres respond to external drivers and to each other?	Mechanisms of particle acceleration in the low corona and the interplanetary medium	STEREO
	<i>Determine the internal coupling processes within the ITM system and the mediation and control of energy and momentum transfer</i>	
	Chemical pathways to radiation processes and global energy balance	TIMED
	Response to geomagnetic storms and solar variability	
What are the precursors to solar disturbances?	<i>Determine the atmospheric response to energetic particles, electromagnetic radiation, and chemical transport</i>	
	Solar spectral irradiance and variability	TIMED
	<i>Are there precursors in the surface magnetic & flow fields?</i>	
	Determine which surface field configurations are most likely to flare	Hinode
How do solar wind disturbances propagate and evolve through the solar system?	Temporal changes preceding large flares & filament eruptions	Hinode
	Magnetic energy storage in the corona from photospheric field extrapolations	Hinode
	<i>How do solar disturbances create particle radiation hazards?</i>	
	Global structure of CMEs and other transients, and how they evolve	STEREO

Recommendations for Solar Terrestrial Probe Program

Origin of Near-Earth Plasma (ONEP)

Understand the origin and transport of terrestrial plasma from its source to the magnetosphere and solar wind.

Plasma of ionospheric origin is now widely recognized as a critical constituent of magnetospheric dynamics, providing the primary source of plasma for the ring current and plasma sheet during active conditions. The key unknown is how this plasma is heated and accelerated so that it may escape Earth's gravitational bounds.

Candidate heating processes include Joule dissipation through ion-neutral collisions, energetic particle precipitation, and wave heating. Information is needed on the sources of energy, the heating and dissipation processes, and characterization of the modes of energy transfer from above and below.



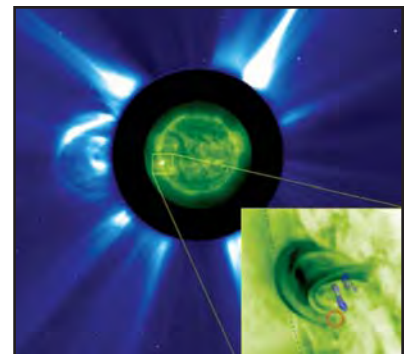
Recommended Mission Class: Small

Solar Energetic Particle Acceleration and Transport (SEPAT)

Understand how and where solar eruptions accelerate energetic particles that reach the Earth.

Solar activity is often linked to the release of highly energetic particles, including heavy ions. The origin and the mechanisms that accelerate particles to high energies close to the Sun are neither fully identified nor understood. Heavy-ion charge states form an equilibrium shaped by the constant interaction with electrons in the strong solar magnetic fields. They are a unique identifier for the site of acceleration and processes between the Sun and the spacecraft.

A strategy for a breakthrough in the area of solar particle acceleration is a mission that can separate the effects of particle transport from pure acceleration signatures. Thus, in situ measurements of energetic particles from multiple vantage points in the inner heliosphere, coupled with advanced particle transport modeling and theory, are needed to resolve this long-standing problem.



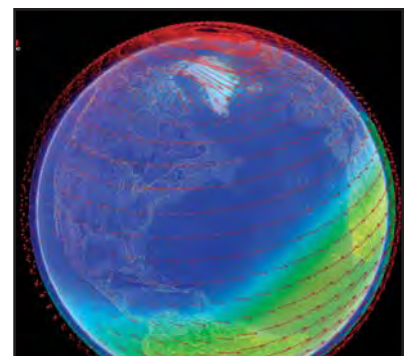
Recommended Mission Class: Small

Ion-Neutral Coupling in the Atmosphere (INCA)

Understand how neutral winds control ionospheric variability.




Measurements of neutral winds are crucial for understanding ionospheric variability; the paucity of such measurements represents the greatest experimental impediment to progress. Previous missions discovered that coupled parameters must be measured to understand the system and showed that the ion and neutral motions depend on prior history of the system, not just the present state.

There are almost no observations of the ionospheric density, composition, and the altitude variation of the neutral winds below 250 km. At low latitudes near 300 km, there are indications that the variability about the mean value is of the same order as the mean value itself. At high latitudes near 300 km, the neutral winds appear to be strongly driven by collisions with ions and electrodynamic coupling to the magnetosphere.



Recommended Mission Class: Medium

Highest Priority STP Science Issues Currently Targeted

How are plasmas and charged particles heated and accelerated?	<i>How are energetic particles transported?</i>		
	How and where solar eruptions accelerate the energetic particles that reach Earth		STP #6 SEPAT
How are planetary thermal plasmas accelerated and transported?	<i>What determines the composition of upwelling and escaping ionospheric plasma?</i>		
	Determine the dissipation processes that heat ionospheric plasmas and the coupling processes that affect planetary ionosphere scale heights		STP #5 ONEP
What governs the coupling of neutral and ionized species?	<i>How are dynamo potentials produced in interaction of atmospheres and magnetized thermal plasmas?</i>		
	Variability in the terrestrial wind dynamo and ionosphere		STP #7 INCA
How do coupled middle and upper atmospheres respond to external drivers and to each other?	<i>Determine the internal coupling processes within the ITM system and the mediation and control of energy and momentum transfer</i>		
	Neutral winds, disturbance dynamo, and equatorial electrojet		STP #7

Living With a Star Flight Program

The Living With a Star (LWS) program was initiated in 2001 to develop the scientific understanding to address the aspects of the connected Sun-Earth system that affect life and society.



The LWS program targets specific aspects of the coupled Sun-Earth-planetary system in a coordinated fashion that affect life and society and that enable robotic and human exploration of the solar system.

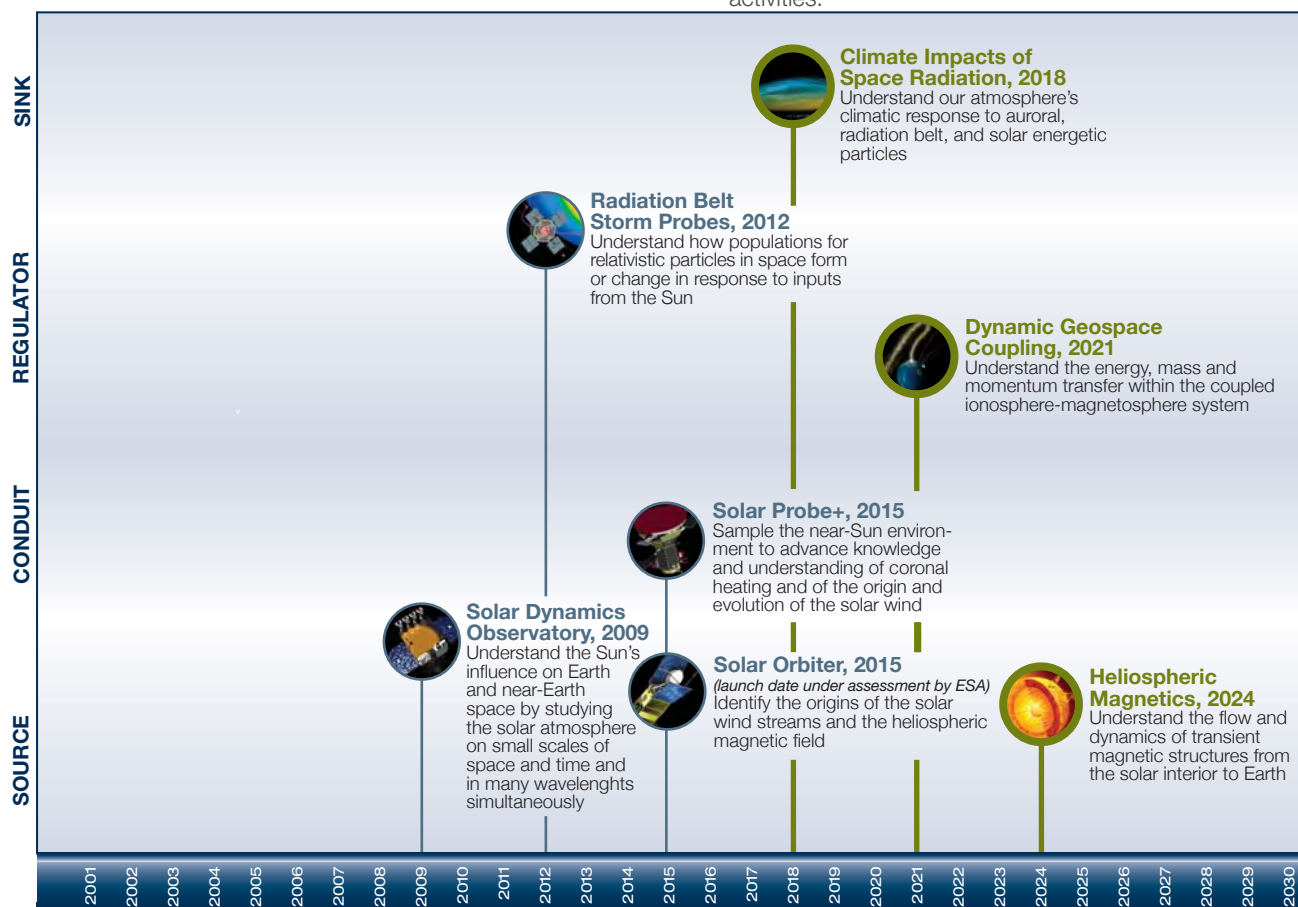
The LWS program emphasizes the science necessary to understand those aspects of the Sun and the Earth's space environment that affect life and society. The ultimate goal is to provide a predictive understanding of the system, almost to the point of predictability, of the space weather conditions at Earth as well as the interplanetary medium. LWS missions are formulated to answer the specific questions needed to understand the linkages among the interconnected systems that impact us. LWS products impact technology associated with space systems, communications and navigation, and ground systems such as power grids. Its products improve understanding of the ionizing radiation environment, which has applicability to human radiation exposure in the Space Station, to high altitude aircraft flight, and to future space exploration with and without human presence. Its

products impact life and society by improving the definition of solar radiation that is a forcing function for global climate change, surface warming, and ozone depletion and recovery.

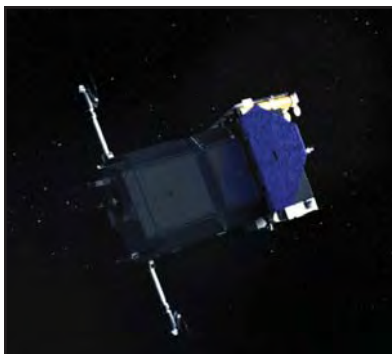
The goal of the LWS program is to understand aspects of the interconnected regions of space, from the Sun's interior through interplanetary space, down to planetary atmospheres that affect life and society, in order to enable the development of a predictive capability of space environments.

The objectives of the LWS program are to:

1. Understand how the Sun varies and what drives solar variability,
2. Understand how the Earth and planetary systems respond to dynamic external and internal drivers, and
3. Understand how and in what ways dynamic space environments affect human and robotic exploration activities.



Missions Currently in Development



Solar Dynamics Observatory (SDO)

Understand the Sun's influence on Earth and near-Earth space by studying the solar atmosphere on small scales of space and time and in many wavelengths simultaneously.

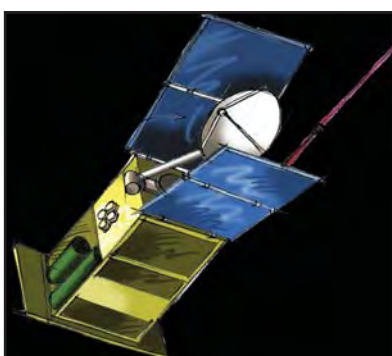
SDO's goal is to understand, driving towards a predictive capability, the solar variations that influence life on Earth and humanity's technological systems by determining how the Sun's magnetic field is generated and structured, and how this stored magnetic energy is converted and released into the heliosphere and geospace in the form of solar wind, energetic particles, and variations in the solar irradiance. SDO will study how solar activity is created and how Space Weather emerges as a product of that activity. Measurements of the interior of the Sun, the Sun's magnetic field, the hot plasma of the solar corona, and the irradiance that creates the ionospheres of the planets are our primary data products.



Radiation Belt Storm Probes (RBSP)

Understand how populations of relativistic particles in space form or change in response to inputs from the Sun.

The RBSP mission will provide unprecedented insight into the physical dynamics of the radiation belts and give scientists the data they need to make predictions of changes in this critical region of space. Two spacecraft will orbit the Earth, sampling the harsh radiation belt environment where major space weather activity occurs and many spacecraft operate. The two spacecraft will measure the particles, magnetic and electric fields, and waves that fill geospace. Only with two spacecraft taking identical measurements and following the same path can scientists begin to understand how the belts separately change in both space and time.



Solar Orbiter

Discover the inner heliosphere and the unexplored polar regions of the Sun.

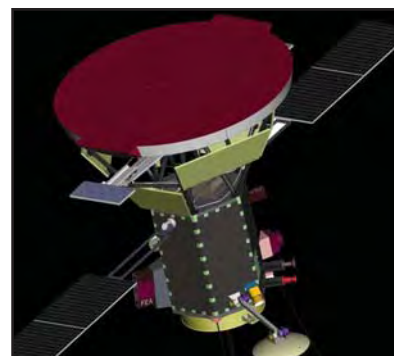
ESA's Solar Orbiter mission is conceived to close within one-fifth of Earth's distance from the Sun to perform a close-up study of our Sun and inner heliosphere. At these distances, the spacecraft will be closer to the Sun than any previous mission and for short periods will almost co-rotate with the surface of the Sun. The goals of this mission are to determine in situ the properties and dynamics of plasma, fields, and particles in the near-Sun heliosphere, to survey the fine detail of the Sun's magnetized atmosphere, to identify the links between activity on the Sun's surface and the resulting evolution of the corona and inner heliosphere, and to characterize the Sun's polar regions and equatorial corona from high latitudes.



Solar Probe +

Discover why the solar corona is so much hotter than the photosphere, and how the solar wind is accelerated.

Solar Probe + will approach as close as nine solar radii of the surface of the Sun, repeatedly sampling the near-Sun environment. By directly probing the solar corona, this mission will revolutionize our knowledge and understanding of coronal heating and of the origin and evolution of the solar wind, critical questions in heliophysics that have been ranked as top priorities for decades. Two of the transformative advances in our understanding of the Sun and its influence on the solar system were the discovery that the corona is hundreds to thousands of times hotter than the visible solar surface (the photosphere) and the development—and observational confirmation—of the theory of the corona's supersonic expansion into interplanetary space as the solar wind. By making the first direct, in situ measurements of the region where some of the most hazardous solar energetic particles are energized, Solar Probe + will make a fundamental contribution to our ability to characterize and forecast the radiation environment in which future space explorers will work and live.



Space Environment Testbeds (SET)

The SET project performs flight and ground investigations to characterize the space environment and its impact on hardware performance in space. A data analysis component supports the development of models, tools, and databases that describe hardware performance [in the presence of a satellite] delete in space. A space flight component supports investigations that lead to a physics-based understanding of the response of technical systems to the varying space environment.



The Balloon Array for RBSP Relativistic Electron Losses (BARREL)

BARREL is a balloon-based mission of opportunity to augment the measurements of the RBSP mission. There will be two campaigns of 5-8 long-duration balloons aloft simultaneously over a one-month period to provide measurements of the spatial extent of relativistic electron precipitation and to allow an estimate of the total electron loss from the radiation belts. Observations are planned for when the balloon-array will be conjugate with the RBSP spacecraft, such that direct comparison is possible between one another. The first campaign is scheduled for 2012, the second for 2013.





Open LWS Science Issues Currently Targeted*

How are plasmas and charged particles heated and accelerated?	<i>How are charged particles accelerated & decelerated?</i>	
	Understand the mechanisms and importance of stochastic acceleration	RBSP
	Determine the importance of seed populations and how they are created	RBSP
How is the solar wind accelerated?	<i>Where does solar wind acceleration occur?</i>	
	Distinguish accelerating processes on the Sun	SO
	Distinguish accelerating processes near the Sun in situ	SP+
What is the fundamental nature of the solar dynamo and how does it produce the solar cycle?	<i>What is the nature of subsurface flows and the subsurface magnetic field?</i>	
	“Relative importance of the two most important regions of dynamo action,	SDO
	Determine the cause of the active longitudes and asymmetric hemispheres”	SDO
What are the precursors to solar disturbances?	<i>Are there precursors observable beneath the solar surface?</i>	
	Observe how the Sun’s magnetic field is generated and structured in its interior and how stored magnetic energy in the corona is released into the heliosphere	 SDO
	<i>What is the morphology of the heliospheric magnetic field?</i>	
What is the magnetic structure of the Sun-heliosphere system?	Determine the origins of solar wind streams and the heliospheric magnetic field	SO
	<i>How do solar disturbances erupt and propagate?</i>	
	Understand the physical processes controlling the heating of the solar corona, the acceleration of the solar wind, and the magnetic release of eruptive activity	 Solar Probe +
How do solar wind disturbances propagate and evolve through the solar system?	<i>How do solar disturbances create particle radiation hazards?</i>	
	Sources, acceleration mechanisms, and transport processes of solar energetic particles	 SO
	<i>Determine the mass input and acceleration/loss processes that control the dynamics of the inner magnetosphere.</i>	
What are the transport, acceleration, and loss processes that control the behavior of planetary magnetospheres?	Determine the major acceleration and loss process for the radiation belts.	 RBSP
	<i>Measure the total solar irradiance and solar spectral irradiance as a function of wavelength and solar cycle</i>	
	Solar X-ray and EUV Spectral Variation	SDO

* Missions in bold are a “primary contributor”, and those in gray “partially contribute”.



Recommendations for Living With a Star Program

Climate Impacts of Space Radiation (CISR)

Understand our atmosphere's response to auroral, radiation belt, and solar energetic particles and the associated effects on ozone.

Generation of odd nitrogen in the thermosphere, especially at high latitude, is well known, but transport processes to the middle atmosphere are poorly understood due to a paucity of measurements.

Changes of odd nitrogen and ozone in response to solar energetic particle events have been observed but are not yet understood. Radiation belt particles penetrate into the mesosphere but the causal linkage with middle atmospheric chemistry is speculative. Changes in ozone alter the thermal budget of the middle atmosphere so that a climate linkage is possible, but, without observations, this cannot be explored.

Dynamic Geospace Coupling (DGC)

Understand how magnetospheric dynamics provides energy into the coupled ionosphere-magnetosphere system.

The coupled ionosphere-magnetosphere system is highly nonlinear and dynamic. Scientists have catalogued the responses of different parts of the system and the general nature of the connections between them. Yet the processes that control the coupling or how the dynamics of one region of this systems of systems drive the dynamics in other regions are not understood.

The next scientific step is to simultaneously probe the dynamics in the magnetosphere and ionosphere. Magnetospheric dynamics can be understood through in situ measurements across spatial scales characteristic of global circulation, while ionospheric dynamics can be remotely probed through auroral imaging. Auroral acceleration and heating change both ionospheric and magnetospheric currents as well as providing ionospheric plasma to the magnetosphere. The nature of these processes, their linked responses to solar wind driving, and the interrelationships between different regions are the key to understanding dynamic geospace coupling.

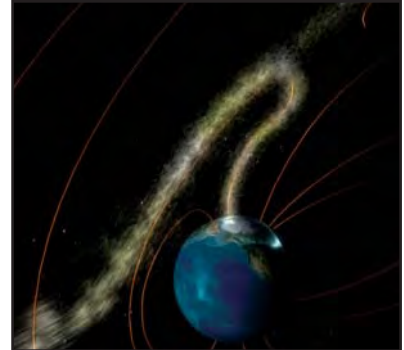
Heliospheric Magnetics (HMag)

Understand the flow and dynamics of transient activity from the solar interior to Earth.

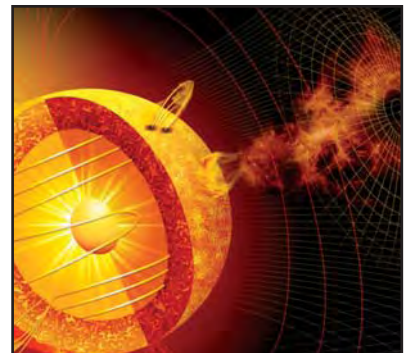
The causes and effects of transient solar activity are a main focus on the path to identifying the precursors and impacts of major solar eruptions. The solar tachocline and convection zone are the origins of strong dynamo magnetic fields. Detailed understanding of magnetic field formation and transport to the visible solar surface is crucial for the identification of triggers of sudden solar activity. Trigger mechanisms may then be linked with the propagation and evolution of existing plasma and fields in the solar corona and inner heliosphere. The synthesis of these elements leads to better physics-based predictive capabilities of space weather. A systematic approach is needed, one that combines the physics of the solar interior with the evolution of the inner heliosphere, ideally from a location that permits observations of the Sun-Earth line.



Recommended Mission Class: Small






Recommended Mission Class: Medium



Recommended Mission Class: Medium



Highest Priority LWS Open Science Issues to Target*

What is the fundamental nature of the solar dynamo and how does it produce the solar cycle?	What is the nature of subsurface flows and the subsurface magnetic field?		
	Properties of subsurface magnetic fields and characteristics of meridional flows		LWS #9
What is the magnetic structure of the Sun-heliosphere system?	How does magnetic variation propagate through the heliosphere?		
	Understand how background magnetic fields influence the flow and dynamics of transient activity		LWS #9 HMag
What are the transport, acceleration, and loss processes that control the behavior of planetary magnetospheres?	What are the processes that control the dynamics of the aurora?		
	Relationship of Alfvén and electrostatic acceleration mechanisms and how they evolve		LWS #8
How do the magnetosphere and the ionosphere-thermosphere systems interact with each other?	How does energy and momentum from the solar wind propagate downward through geospace to Earth?		
	Understand how magnetospheric dynamics provides energy into the coupled ionosphere-magnetosphere system.		LWS #8 DGC
How do long-term variations in solar energy output affect Earth's climate?	Determine the atmospheric response to energetic particles, electromagnetic radiation, and chemical transport		
	Understand our atmosphere's response to auroral, radiation belt, and solar energetic particles, and the associated effects on ozone		LWS #7 CSIR

* Missions in bold are a "primary contributor", and those in gray "partially contribute".

Explorer Flight Program

The Explorer Program provides frequent flight opportunities for world-class scientific investigations from space to address Heliophysics and Astrophysics Space Science goals.

The Explorers Program is the oldest continuous program in NASA. It is comprised of a series of space science missions that are independent, but share the efficiencies of a common funding and management structure. The goal is to investigate focused Astrophysics and Heliophysics science that is driven by new knowledge, discoveries, and evolving science priorities using relatively low-cost, rapid-response, fully competed Principal Investigator (PI)-led missions.

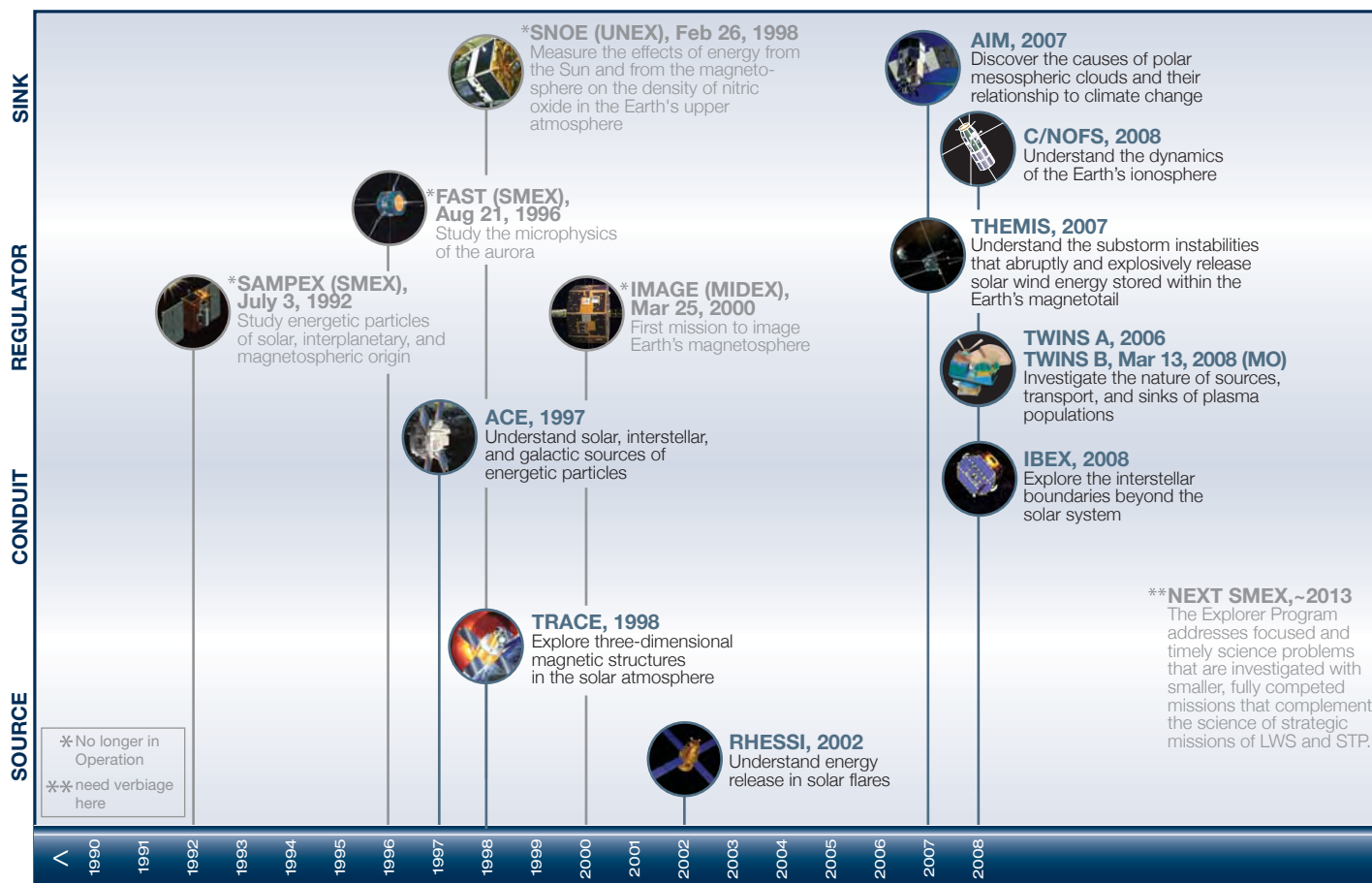
The specific mission objectives are defined by the PIs in their proposals and are approved by NASA at Mission Confirmation. The intent is to conduct scientific investigations of modest and focused programmatic scope that can be developed relatively quickly, generally in 36 months or less, and executed on-orbit in less than 2-3 years.

The objectives of the Explorer program:

1. Are responsive to new knowledge, technology, and science priorities.
2. Are competed within the science community.
3. Occur with regularity and high frequency.
4. Are low-cost and have a short development cycle.



The Explorer missions are a regularly recurring opportunity to fly exciting new missions, selected by peer review for the best science with a relatively short response time, utilizing state-of-the-art instrumentation. The regular launch cadence is vital for the progress of Heliophysics. The recent decline in the Explorer Program budget is reflected in its lower launch cadence and adversely impacts the progress of Heliophysics science.



Explorer missions play a major role in the ability of the Heliophysics Division to fulfill its objectives. The mission results fill important science gaps in the prescribed program. As such, it is an indispensable element of the strategic roadmap plan. These investigations target very focused science topics that augment, replace, or redirect strategic line missions. Highly competitive selection assures that the best strategic science of the day will be accomplished.

Open Explorer Science Issues Currently Targeted*

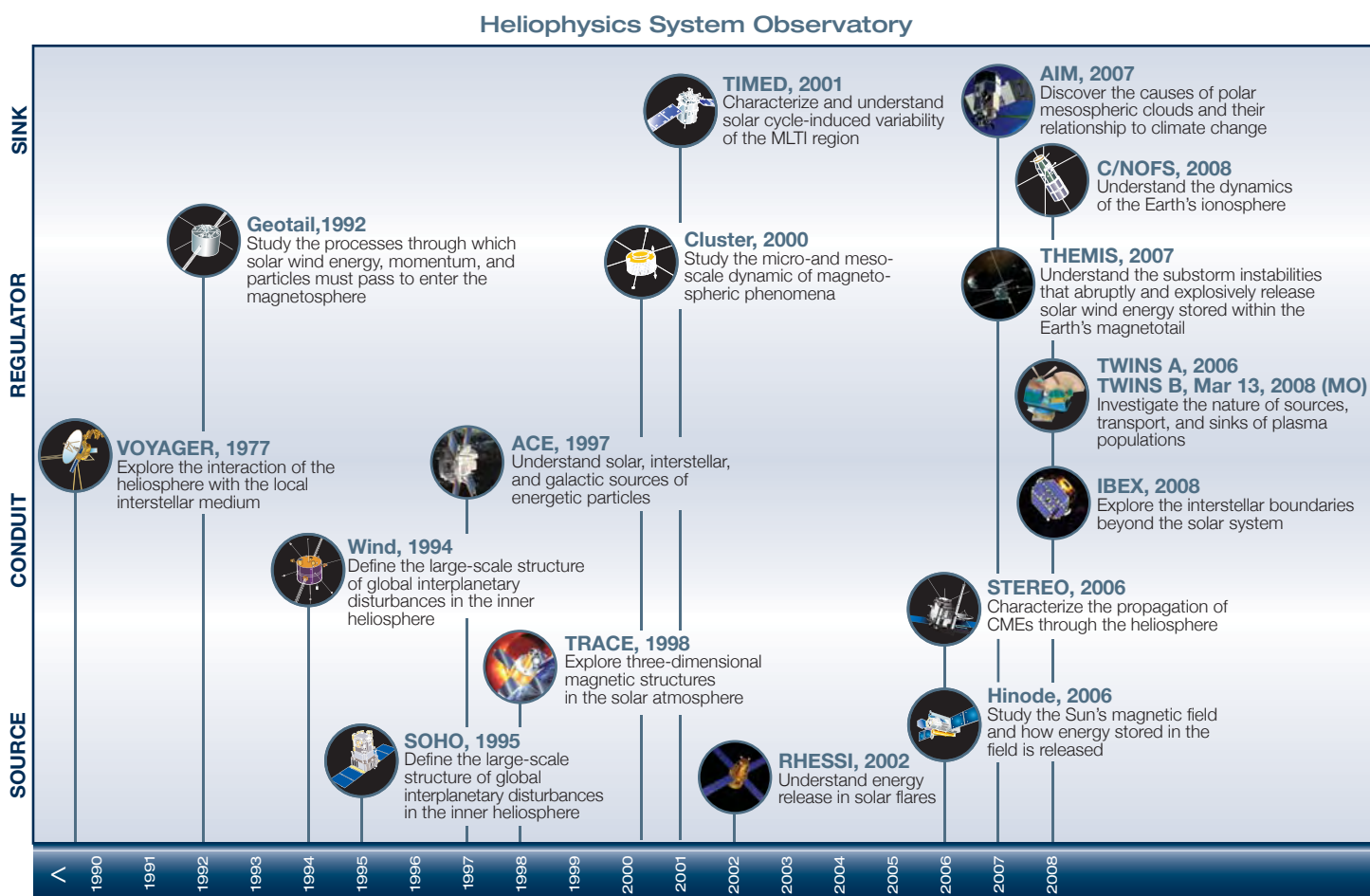
What are the fundamental physical processes and topologies of magnetic reconnection?	<i>What are the magnetic field topologies for reconnection?</i>	
	Discover the dynamics, scale size, and energy balance of distant magnetotail reconnection and turbulence processes.	ARTEMIS
How is the solar wind accelerated?	<i>What are the sources of energy for solar wind acceleration?</i>	
	Study processes that accelerate the solar wind and generate coronal mass ejections	CPEXX
	Reveal the dynamics of the solar chromosphere and transition region	IRIS
How do coupled middle and upper atmospheres respond to external drivers and to each other?	<i>Understand the processes that couple the ITM system to the atmosphere and drive variability</i>	
	Understand the temperature and composition in the ionosphere including those induced by wave and tidal processes	GOLD
	<i>Understand the global and local electrodynamics of the ITM system in response to geomagnetic dynamics</i>	
	Global characteristics and small-scale physics of plasma irregularities	CINDI
What is the composition of matter fundamental to the formation of habitable planets and life?	<i>What is the composition of material entering, and interacting with, our solar system? (e.g., interstellar medium, galactic and anomalous cosmic rays)</i>	
	Measure and compare the composition of several samples of matter, including the solar corona, the solar wind, and other interplanetary particle populations, the local interstellar medium, and galactic matter	ACE
What is the magnetic structure of the Sun-heliosphere system?	<i>What is the role of the interstellar magnetic field?</i>	
	Determine the direction of the ISM field and its influence on particle acceleration in the heliosheath	IBEX
How do solar wind disturbances propagate and evolve through the solar system?	<i>How do solar disturbances erupt and propagate?</i>	
	Propagation path and evolution of CMEs to 1 AU, including how these conditions evolve through the solar cycle	ACE
	<i>How do solar disturbances create particle radiation hazards?</i>	
How do the heliosphere and the interstellar medium interact?	Investigate particle acceleration and energy release in solar flares	RHESSI
	<i>What are the properties of the termination shock, heliopause, any bow shock, and the conditions of the local interstellar medium?</i>	
	Map the global properties of the termination shock and heliosheath.	IBEX
What are the transport, acceleration, and loss processes that control the behavior of planetary magnetospheres?	<i>Establish the global connectivities and causal relationships between processes in different regions of the Earth's magnetosphere</i>	TWINS
	<i>Determine the processes that control mass and energy storage, conversion and release in the magnetotail</i>	
	Substorm initiation location	THEMIS
	Relate the aurora to magnetospheric drivers.	THEMIS
What is responsible for the dramatic variability of the Ionosphere-Thermosphere-Mesosphere region?	<i>Determine the seasonal dynamics of the Ionosphere-Thermosphere system driven by lower atmosphere processes.</i>	
	Discover how winds and the composition of the upper atmosphere drive the electrical fields and chemical reactions that control the Earth's ionosphere	NICE
How do long-term variations in solar energy output affect Earth's climate?	<i>Quantify solar cycle and secular change in the middle atmosphere, thermosphere, and ionosphere</i>	
	Determine why polar mesospheric clouds form and vary	AIM

* Missions in bold are a "primary contributor", and those in gray "partially contribute".

The Heliophysics System Observatory

The HSO is a fleet of widely deployed solar, heliospheric, geospace, and planetary spacecraft that work together to discover the fundamental physical processes at work throughout the complex, coupled system. Although not an explicit budget line item, it is nevertheless a central program element in the Integrated Research Strategy of the 2003 Decadal survey and in this roadmap.

The HSO enables the study of system science from the diverse measurements across distributed spatial scales that are linked by a variety of improving models that fill in the gaps of our observations and validate our theoretical understanding of Heliophysics. Ultimately a combination of Heliophysics knowledge and a healthy HSO will facilitate an operational capability to predict space weather. The HSO arose without intentional planning from a series of individual missions, but opportunity exists now to deliberately evolve this distributed observatory to better meet the needs of Heliophysics and the Vision for Space Exploration.



Additional Open Science Issues that can be addressed by extending current assets.*

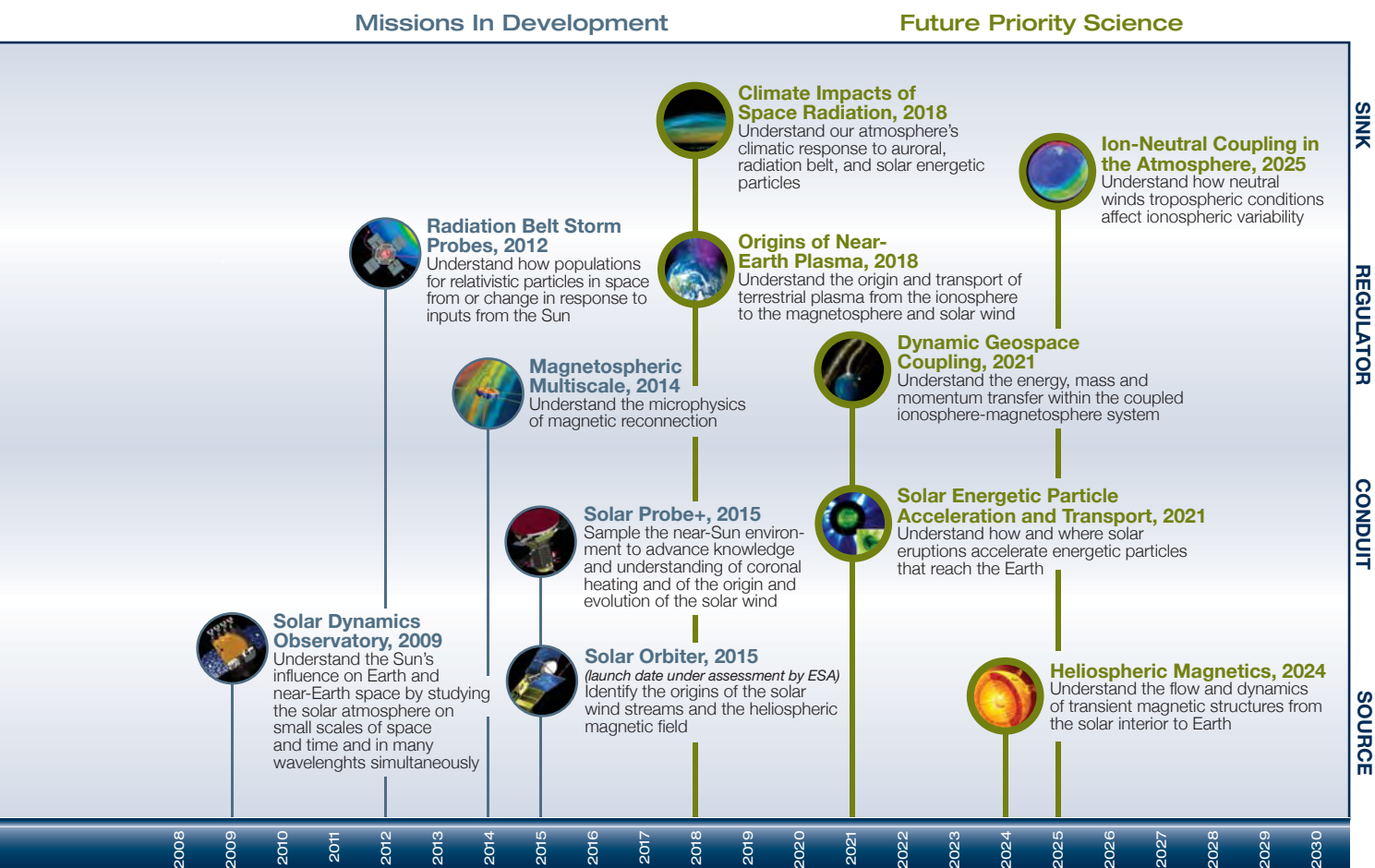
What are the fundamental physical processes and topologies of magnetic reconnection?	<i>What are the magnetic field topologies for reconnection?</i>	
	Quantify the characteristics of reconnection (i.e. scale sizes, geometries, candidate processes, locations, consequences, and frequencies of occurrence).	Several Missions
How are plasmas and charged particles heated and accelerated?	<i>How are charged particles accelerated & decelerated?</i>	
	Understand the mechanisms and importance of diffusive shock acceleration	Several Missions
	<i>How are energetic particles transported?</i>	
	Connect the particles producing solar radio bursts back to the corona	RHESSI
How are planetary thermal plasmas accelerated and transported?	Determine acceleration mechanisms for anomalous and galactic cosmic rays	Voyager, IBEX
	<i>How are thermal plasmas accelerated and transported by electromagnetic fields?</i>	
	Determine role of induction fields and wave heating processes	THEMIS
	<i>What determines the composition of upwelling and escaping ionospheric plasma?</i>	
What is the composition of matter fundamental to the formation of habitable planets and life?	Determine the drivers of energy deposition	Cluster
	<i>What is the composition of particles emanating from the Sun?</i>	
What are the precursors to solar disturbances?	Solar energetic particle abundances and solar wind CNO charge-state separation	Several Missions
	<i>Are there precursors observable beneath the solar surface?</i>	
What is the magnetic structure of the Sun-heliosphere system?	Understand the causes and mechanisms of CME initiation and propagation	SOHO
	<i>What is the relationship between closed and open flux?</i>	
	Discover whether open flux can disconnect from the Sun in interplanetary space	Wind STEREO
	<i>What is the role of the interstellar magnetic field?</i>	
How do solar wind disturbances propagate and evolve through the solar system?	Determine the direction of the ISM field and its influence on particle acceleration in the heliosheath	Voyager
	<i>How do solar disturbances erupt and propagate</i>	
How do the heliosphere and the interstellar medium interact?	Propagation path and evolution of CMEs to 1 AU, including how these conditions evolve through the solar cycle	Wind
	<i>What are the properties of the termination shock, heliopause, any bow shock, and the conditions of the local interstellar medium?</i>	
How are mass and energy transferred from the heliosphere to a planetary magnetosphere?	Discover the properties of the termination shock	Voyager
	<i>What are the relative contributions of processes which transfer particles and energy across magnetospheric boundaries</i>	
	Mechanisms controlling the entry and transport of plasma into the magnetosphere	Geotail
	Three-dimensional studies of plasma structures at the bow shock, magnetopause, dayside cusp, magnetotail and solar wind	Cluster

* Missions in bold are a “primary contributor”, and those in gray “partially contribute”.

The Evolving Heliophysics System Observatory

The HSO will continue to evolve as new spacecraft join and older ones retire or change their operating modes. Missions both in their prime phase and in extended phases (supported by the Heliophysics Mission Operations and Data Analysis (MO&DA) program) provide the variety of observation posts needed to study Sun-solar system connections. A great strength of this fleet is that it is regularly evaluated and reviewed to maximize the return on Agency investments. This Senior Review process determines which spacecraft are most necessary to meet the needs of the Heliophysics program as defined by the community-developed Strategy Roadmap. The criteria for continuation include relevance to the goals of the Heliophysics Division; impact of scientific results as evidenced by citations, awards, and press releases; spacecraft and instrument health; productivity and vitality of the science team (such as high quality and impact published research, training of younger scientists, education and public outreach); promise of future impact and productivity (due to uniqueness of orbit and location or solar cycle phase for example); and broad accessibility and usability of the data.

The HSO of the future will of course change as old missions are retired and new ones are launched. We have inherited a very capable suite of satellites. It is important to keep in mind that regardless of the great assets presently in space for



the study of our discipline, they are all temporary. The Open Science Questions are many and a continued distributed observing capability will be required into the foreseeable future. New missions are needed and they are needed in a timely manner. Launches must occur with a reasonable frequency and new approaches must be used to lengthen the lifetime of newly launched missions. In this way can we meet the goals, aspirations and potential of Heliophysics.

Open Science Issues left for Future Explorers or Partnership Initiatives

What are the fundamental physical processes and topologies of magnetic reconnection?	<i>What are the fundamental physical processes of reconnection?</i>	
	Microphysics of reconnection at the Sun: Do the processes differ from those at Earth? What triggers fast reconnection in large flares?	Remaining to be addressed
	<i>How do the large-scale topologies of magnetic reconnection affect microphysical processes, and vice-versa?</i>	Cross-Scale/SCOPE
How is the solar wind accelerated?	<i>What is the role of waves and dissipation in solar wind acceleration?</i>	
	Understand the energy dissipation modes that dominate heating	Remaining to be addressed
	Determine the importance of small-scale magnetic reconnection	Remaining to be addressed
What is the composition of matter fundamental to the formation of habitable planets and life?	<i>What is the composition of material entering, and interacting with, our solar system? (e.g., interstellar medium, galactic and anomalous cosmic rays)</i>	
	Determine the composition of low-energy galactic cosmic rays, the local interstellar plasmas, and interstellar dust populations	Interstellar Probe
What are the precursors to solar disturbances?	<i>Are there precursors in the chromosphere and corona?</i>	
	Magnetic energy storage in the corona from chromospheric, transition region or coronal field measurements	Solar C
How do solar wind disturbances propagate and evolve through the solar system?	<i>How do solar disturbances erupt and propagate?</i>	
	Evolution of source conditions eruptions over the 3-D Sun and inner heliosphere	Remaining to be addressed
	Impact of CMEs and other solar wind disturbances on the global heliosphere	Remaining to be addressed
	<i>How do solar disturbances create particle radiation hazards?</i>	
How do the heliosphere and the interstellar medium interact?	Discover which magnetic and shock structures in the corona accelerate energetic electrons	Remaining to be addressed
	<i>What are the properties of the termination shock, heliopause, any bow shock, and the conditions of the local interstellar medium?</i>	
	Discover the properties of the local interstellar medium, how it changes with time, and determine the implications for our solar system	Interstellar Probe
How are mass and energy transferred from the heliosphere to a planetary magnetosphere?	Determine whether the termination shock or heliosheath accelerates anomalous cosmic rays	Remaining to be addressed
	<i>What is the global response of the magnetosphere and aurora to the solar wind?</i>	
	<i>What controls mass and energy transfer at other magnetospheres.</i>	
What is responsible for the dramatic variability of the ionosphere-Thermosphere-Mesosphere region?	Impact of magnetosphere size, rotation rate, orientation and solar wind IMF on the transfer of mass and energy	Remaining to be addressed
	<i>Discover the connections between spatial and temporal scales in the Ionosphere-Thermosphere system.</i>	
	<i>Understand the electrodynamics that couple the magnetosphere and ionosphere-thermosphere.</i>	Remaining to be addressed
How do the magnetosphere and the ionosphere-thermosphere systems interact with each other?	<i>How does energy, mass and momentum propagate upward through geospace?</i>	
	Poleward transport of ionospheric plasma energizing magnetic storms	
	Temporal/spatial distribution of ion outflow	Remaining to be addressed
	Dependence of heating rates/outflow on scale size of magnetospheric input, solar flux	

Role of Partnerships

The urgent need for progress across a range of topic areas coupled with limitations of resources underscores the value of partnerships to increase scientific return. Partnerships with other Divisions within NASA, with other government agencies, and with international partners have already demonstrated their value in missions such as Messenger, CINDI/CNOFS, and Cassini. Some opportunities for future collaboration are highlighted here.

Intra-NASA Partnerships

Heliophysics benefits from missions in the Planetary Science Division and the Exploration Systems Mission Directorate (ESMD). New opportunities are clearly evident in the ESMD Lunar Reconnaissance Orbiter (LRO). It is the first mission in NASA's plan to return to the Moon and then to travel to Mars and beyond. LRO will launch in 2009 with the objectives of finding safe landing sites, locate potential resources, characterize the radiation environment, and demonstrate new technology.

Lunar Atmosphere and Dust Environment Explorer (LADEE) will orbit the Moon and its main objective is to characterize the atmosphere and lunar dust environment and "determine the global density, composition, and time variability of the fragile lunar atmosphere before it is perturbed by further human activity." [The NRC's report, *The Scientific Context for the Exploration of the Moon* (NRC, 2007)]

The Mars Program has planned launches throughout the coming decade to study the geology and atmosphere of Mars. The Mars Science Laboratory (MSL) and Mars Aeronomy missions are of particular relevance.

National Agency Partnerships

Recently, heliophysics instruments addressing some of the scientific goals enunciated in this roadmap have found ride opportunities on non-NASA payloads. Two Wide-Angle Imaging Neutral-Atom Spectrometers (TWINS) will enable the three-dimensional visualization and the resolution of large-scale structures and dynamics within the magnetosphere for the first time. In collaboration with the U.S. Air Force, the Coupled Ion Neutral Dynamic Investigation (CINDI) was supplied by NASA as part of the payload for the Air Force C/NOFS satellite. CINDI is investigating the study of unique plasma bubbles that have the potential to disrupt critical radio signals.

Commercial Ride Opportunities

The commercial space market provides about half of the global demand for launch vehicles. The 2004 FAA/COMSTAC forecast of commercial demand indicates that the launch rate will remain static at ~22 per year from 2000 until 2013. Some of the launch organizations have indicated a willingness to accommodate piggy-back science payloads on their spacecraft. This could be an important route to orbit for some Heliophysics payloads.



Lunar Reconnaissance Orbiter (LRO)



Mars Missions Beyond 2009



Air Force Communication/Navigation Outage Forecast System (C/NOFS) Satellite

Potential International Partnerships

The International Living With a Star (ILWS) program was established in January 2002 by the Interagency Consultative Group (IACG). The charter for ILWS is to “stimulate, strengthen, and coordinate space research to understand the governing processes of the connected Sun-Earth System as an integrated entity.” More than 25 contributing organizations are listed at <http://ilws.gsfc.nasa.gov>. ILWS offers opportunities for cooperation between national space agencies for spaceflight opportunities.

Foreign contributions to NASA payloads, such as the Huygens lander on the Cassini mission or the joint development of the SOHO or Hinode missions, have significantly improved the quality of many science missions. Strengthening the technical teamwork between the United States and our partners permits activities that could not be achieved separately. Examples of potential international partnerships are listed below.

SOLAR-C

JAXA is considering a follow-on to the highly successful Hinode mission. Two potential science issues are under consideration: Option A: out-of-ecliptic observations of the Sun’s polar and equatorial regions to investigate properties of the polar dynamo, or Option B, high spatial resolution, high throughput, high cadence spectroscopic observations to investigate the magnetism of the Sun and its role in heating the solar corona.

CROSS-SCALE/SCOPE

The Cross-Scale and SCOPE missions will investigate the dynamics of space plasma interactions by simultaneously measuring those plasma characteristics at three length scales – electron kinetic (10 km), ion kinetic (100s km), and magneto-hydrodynamic fluid scales (1000s km) at the Earth’s bow shock and magnetosheath, and within the Earth’s magnetotail. Cross-Scale is led by ESA, and SCOPE by JAXA. Together these missions seek to understand the interactions between nonlinear phenomena operating between these scale lengths.

ORBITALS

The Outer Radiation Belt Injection, Transport, Acceleration, and Loss Satellite (ORBITALS) is a CSA-sponsored mission to understand the acceleration, global distribution, and variability of energetic electrons and ions in the inner magnetosphere. Together with other ILWS missions, such as NASA’s RBSP, ORBITALS will provide a unique and global view of the inner magnetosphere.

INTERSTELLAR PROBE

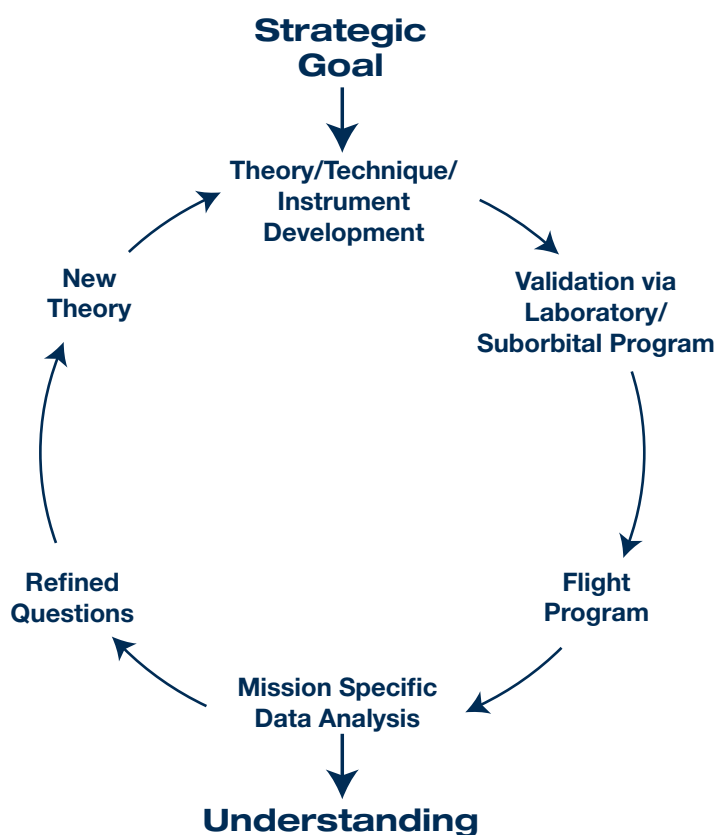
A science investigation to explore the interstellar boundary was ranked highly by the Roadmap committee. But the cost of implementing a mission to meet the science objectives would exceed the resources of the Division without undermining the central theme of the roadmap, which is system science. Hence, a partnership may be the best way to achieve the science objectives.

The next logical step in exploring the unknown would be to sample directly the interstellar medium that lies beyond the extended solar atmosphere. The solar wind and magnetic field keep the unique plasma of the interstellar medium outside the heliosphere. A partnership mission to interstellar space would continue the tradition of Explorer 1 by sampling a widely unknown medium with its unique dynamics and composition. It would also allow us for the first time to access the regime of low-energy cosmic rays that helps us understand cosmic particle acceleration processes.

Recommendations for Supporting Research Programs

The Supporting Research programs for the Heliophysics Division form the bedrock from which new knowledge and understanding flow, and enable the ultimate prediction of space environments. Here, we describe the objectives for each of the programs and the specific role each plays in the integrated program of the Division. The research programs are the Guest Investigator (GI), the LWS Targeted Research and Technology (TR&T), the Supporting Research and Technology (SR&T), and the Theory Program. Investment in the technology needed to make the measurements and manage the data required to answer the unresolved questions are made through the SR&T (instruments), TR&T (models) programs.

The cycle on this page illustrates the functions of the programs in the scientific method. It reinforces the concept of an integrated research process—a central theme of the Division. A careful allocation of resources across the full set of programs is needed to maintain the effectiveness of the cycle.



SR&T Contributions to Scientific Process

- Strategic Goal
- Requires Development of
 - Theory
 - Data Analysis Techniques
 - Models
 - Instruments
- Which are tested via the
 - Laboratory and/or
 - Suborbital Program
- Leading to Flight Programs and Analysis of Mission Data
- Which Leads to Either
 - Greater Understanding of the Goal or
 - A New Cycle
- Which Then Leads to *Achievement of the Goal*

Theory Program

The Theory program is the intellectual compass of the program. It leads the way to new understanding of previous investigations and drives the science concepts for future strategic missions. The Theory program supports large PI-proposed team efforts that require a critical mass of expertise to make significant progress in understanding complex physical processes with broad importance. It is expected that this program will support the six high-priority science Targets in the recommended science queue.

Supporting Research and Technology

The SR&T program is the forward planning arm of the Heliophysics research program. Results of investigations in the program guide the direction and content of future science missions. The primary components are R&A, instrument development, and low-cost access to space (LCAS). The R&A component provides theory and model development and the analysis of spacecraft data. The instrument concept development is closely tied to R&A. Its purpose is twofold—quick transition of new technology or instrumentation ideas into effective tools for the flight program and reduction of development costs for missions in development. The LCAS program uses rockets and balloons for the advancing the readiness level of instruments and produces cutting-edge science discoveries in important areas of Heliophysics.

Guest Investigator

The GI program is a critical component of Heliophysics System Observatory. The GI addresses science questions using data from the HSO. The GI program enables a broad community of Heliophysics researchers in universities and institutions to use the HSO data in innovative scientific investigations pursuing the goals of this roadmap. The focus of competitively selected research continuously evolves to ensure that the most important questions are addressed.

Targeted Research and Technology

The LWS TR&T component uniquely satisfies two critical LWS needs—it addresses unresolved questions that cross the usual boundaries between scientific disciplines and between research techniques, and it develops the specific, comprehensive models focused to understand Heliophysics as a system, in particular those that have an applied aspect such as space weather operational forecasting and nowcasting. The targeted questions are recommended on an annual basis by a TR&T Steering Committee. The specific models that are supported are made available for use by the community via strategic tools (e.g., at the Community Coordinated Modeling Center. (CCMC) for use by the scientific community and for evaluation for potential transition to operations.

Virtual Observatories

The Virtual Observatory (VO) program is designed to develop an integrated approach to scientific R&A by enabling the use of diverse datasets via the Web in an easily accessible way. This approach will reduce the exclusivity of NASA mission data and associated data products including models and theoretical predictions. The VO data and products are co-located with the relevant expertise, but accessible to the entire community. The VOs are a whole new approach in the curation of these data assets, which is essential in advancing our understanding of the Heliophysics system.

Mission Operations and Data Analysis

Progress in space science is sparked by observations, which also provide the “ground truth” to test simulations and models. It is essential that observations be properly recorded, analyzed, released, and documented, and rapidly turned into scientific results. Stringent budget environments and associated declining budgets have been somewhat compensated by improvements in information technology making data analysis more efficient; however, the full spectrum of operations and data analysis for missions extends well beyond data analysis.

For Heliophysics missions, the science teams must ensure well-calibrated data throughout the operational phase of the mission. During the mission prime phase, the instrumental characterization task is turned into a semi-autonomous process. However, degradation and other changes of the instrument require continuous monitoring and alteration of algorithms and data processing software by cognizant teams. The Heliophysics Division has recognized these patterns and funds these activities in the MO&DA program. MO&DA funds for the mission teams undergo a regular competitive process, the Senior Review (see app. E), where the level of support is adjusted according to the anticipated scientific productivity and mission maintenance requirements.

The Roadmap Team strongly endorses the MO&DA program that supports turning raw measurements into data products for use in the scientific community. It also endorses the continuation of effective utilization of calibrated data through competitive grants in the GI program, the SR&T program, and the TR&T program that generate tangible scientific results from the rich data sets of the Heliophysics system.

**Heliophysics Virtual
Observatories currently
supported:**

Virtual Cosmic Ray
Observatory (VICRO)

Virtual Heliospheric
Observatory (VHO)

Virtual Ionosphere,
Thermosphere, Mesosphere
Observatory (VITMO)

Virtual Magnetospheric
Observatory (VMO)

Virtual Model
Repository (VMR)

Virtual Radiation Belt
Observatory (VIRBO)

Virtual Solar
Observatory (VSO)

Data Centers

System-level observations and interpretation require new concepts for data manipulation and exploitation. These changes are being driven by several factors. Information from a single spacecraft vantage point is being replaced by multispacecraft distributed observatory methods, and adaptive mission architectures termed “Sensor Webs” that require computationally intensive analysis methods. Future explorers far from Earth will need real-time data assimilative technologies to predict space weather. Modeling will be an integral element of future mission data products. Other modeling efforts will assimilate data collected by multiple missions into coherent visualizations of broader physical systems. Well-managed archives, virtual observatory systems, and the vigorous application of knowledge support tools are central to achieving the major Heliophysics science goals in the coming decades.

Some groundwork for these activities has begun; a confluence of new technologies (internet, XML, and Web services, broadband networking, high-speed computation, distributed grid computing, ontologies, and semantic representation) is dramatically changing the data landscape. Distributed data and computing resources are being linked together for a more rigorous approach in the verification and validation of predictive models.

Examples include the Columbia supercomputer, which uses 10,240 Intel Itanium-2 processors and provides an order of magnitude increase in NASA’s computing capability, and the VO programs, which will provide pattern and feature recognition to allow large datasets to be mined for events, particularly those detected by multiple platforms.

The VO program now includes several prototype heliophysics virtual observatories listed at the side. As these and other virtual observatories come online, they will provide seamless access to all of the heliophysics mission data, essential for new cross-cutting discoveries that will open up the heliophysics frontier. The VMR also complements the existing large multidisciplinary modeling efforts that are also essential for future cross-disciplinary advances. Organizations such as NASA’s CCMC, the NSF-funded Center for Integrated Space Weather Modeling (CISM), and the Center for Space Environment Modeling (CSEM) at the University of Michigan are producing integrated models, transitioning research tools into operational infrastructures, and building software frameworks that link models.

Future progress will require a carefully designed systems architecture to provide the necessary synergism among robust data sets, state-of-the-art models and simulations, high-data-rate sensors, and high-performance computing. The emerging linkage of rich data sets, high-performance computing, models, and sensors will lead to even greater scientific understanding of how our the realm of heliophysics operates as a system and how we can enable a research-supported space weather capability.

Theory and Modeling

Theory and modeling forms a major part of our strategy for understanding the Heliophysics system. The advancement of knowledge and progress of transitioning science products to applied and operational environments are significantly driven by new theories and enabled by newly created models.

Heliophysics by its very nature must contend with a huge range of energy, spatial, and temporal scales in an interconnected large and very complex system. As observations lead to discoveries, a more detailed picture of the heliophysics system is painted with ever-increasing amounts of data. The role of theory and modeling is becoming more important: (1) The complex coupled heliophysics system can best, and perhaps only, be understood via theories that can be modeled and validated or constrained by observations, (2) future mission objectives are driven by the questions that theories pose and predictions that models make, and (3) the advanced mathematics used to understand the heliophysics system, such as coupled nonlinear equations, can be applied to other areas of science.

A strong and robust theory program will enhance the value and planning for the priority science Targets recommended in this roadmap. The program should support theory and modeling teams of sufficient size and capability to enable significant progress in Target science areas. The process of determining what aspect of heliophysics is to be investigated next requires a strong scientific rationale that comes from theories and models.

Heliophysics provides a unique opportunity to advance incredibly difficult predictive and modeling capabilities that can have far-reaching applications. This is because of the complex and coupled nature of heliophysics science, and the amazing detail of the observations made with a myriad of technologies and across a huge range of scales. This creates the unique opportunity to model heliophysics plasmas using very advanced mathematics that require cutting-edge processing techniques.

Low-Cost Access to Space

The LCAS program, whose key elements are the sounding rocket and balloon programs, is an essential component of our research strategy. LCAS investigations make cutting-edge science discoveries using state-of-the-art instruments developed in a rapid turnaround environment. Like Explorer missions, LCAS investigations address important open science questions, thereby augmenting the science accomplished in the strategic line missions. These investigations, selected for the best science, serve three additional purposes that cannot be adequately addressed in other flight programs: the training of experimental space physicists and engineers, the development and flight verification of new instrumentation and methods, and the investigation of coupling between the troposphere/stratosphere/magnetosphere with the ionosphere/thermosphere between 80 km and 200 km altitude.



The scientific relevance of the rocket program is illustrated in the following examples:

NASA's first "tailored" rocket trajectory revealed downward winds over an auroral arc, defying the usual presumption that Joule heating would drive neutral upwelling in the regions of arcs. Observed as the payload traversed a stable auroral arc, the results came as a complete surprise, suggesting upper atmosphere gravity waves dominate the physics of the interaction of aurora with the thermosphere.

In a remote launch campaign at Kwajalein Atoll near the equator, recent sounding rockets provided the first vertical profiles of the electrodynamics at the onset of equatorial "spread-F," an ionospheric instability that generates a broad spectrum of irregularities that have profound space weather implications. The rockets also revealed the presence of bottomside waves that could be the sought-after "trigger" of the instability.

In the area of solar physics, the Extreme Ultraviolet Normal Incidence Spectrograph (EUNIS) sounding rocket observations provided unprecedented high temporal resolution results that challenge existing models of the corona. Probing the structure and dynamics of the inner solar corona with a cadence ~ 2 s allowed unprecedented studies of evolving and transient structures, including measurements of both upflows and downflows of up to 40 km/s in a coronal bright point at temperatures in excess of 2×10^6 K, the highest temperatures recorded in such regions.

A high-altitude auroral zone experiment will be the first attempt at a quantitative investigation of the role of Alfvénic processes in particle acceleration. Alfvén waves have been implicated as a critical component of particle acceleration in space plasmas and as a mass source for the magnetosphere.

Finally, another key feature of the sounding rocket program is its ability to carry out rocket flights under satellites to provide critical calibrations and correlative measurements.

The second component of LCAS is that of balloon missions, which have an outstanding record of scientific discoveries. For example, the solar telescopes on the RHESSI Explorer mission used hard X-ray imaging spectroscopy, high-resolution nuclear gamma-ray line spectroscopy, and gamma-ray line flare imaging to observe the surprising energy release process in solar flares in greater detail than ever before. Furthermore, independent balloon payloads using solar power and Iridium telemetry have been developed to measure relativistic electron precipitation (REP). This system will be used to characterize the REP losses in support of NASA's Radiation Belt Storm Probe satellites in two campaigns, each of which consists of 20 payloads individually lasting at least 1-2 weeks each.

The LCAS program provides important hands-on training for engineers and scientists needed by NASA and the Nation in the future. The program involves numerous undergraduate and graduate students from diverse institutions. Graduate students can participate in the entire life cycle of a scientific space mission, from design and construction to flight and data analysis—something no other flight program can do. The rocket program alone has resulted in more than 375 Ph.D.s. In addition, a rocket or balloon experiment offers the chance for younger scientists to gain the project management skills necessary for more complex missions. The combination of unique science, advanced instrument development, and training makes LCAS a critical path item for achieving NASA's national space science goals.



Develop Technologies to Enable Exploration and Discovery in Heliophysics

Innovation is the engine that drives scientific progress. The invention, development, and application of new technologies lead to new windows into nature's works. Heliophysics is a lively field that applies new technology and thus achieves the return of never-before-seen information. Heliophysics fosters a feedback loop between scientists specializing on data analysis, modeling, and instrument developers so as to uncover the missing links of the larger Heliophysics system picture. This systematic quest for discoveries leads to new interpretations and theories that make predictions. Predictions spark the need for testing, fueling the need for new, focused measurements and technologies. Predictions and forecasts can have immediate applications, adding to the scientific arsenal that deals with the variability in the solar terrestrial environment.

Naturally, deeper understanding of the Heliophysical system emerges and so do applications that mitigate the effects of adverse space weather on society.

To pursue a rigorous study of the Heliophysical system, we recommend rapid development and infusion of new, mission-enabling technologies. Many new technologies we require have a specific Heliophysics focus, but there are also mission-enabling technologies with cross-disciplinary character for which we recommend Heliophysics participation.

Heliophysics Technology:

The ability to achieve the recommended science Targets and those of future missions beyond this roadmap timetable would be greatly enhanced with technology developments in two key technology areas—instrument development and software development. Existing programs support instrument development as a subset of SR&T. Other parts of this program, along with the Heliophysics Theory, LWS TR&T, and the Heliophysics GI program support software development for modeling the Heliophysics system. The LCAS, which includes balloon and sounding rocket investigations, also furthers instrument development, but serves only a part of the Heliophysics community. The technologies identified below are deemed to provide the best return on investment with regard to addressing the prioritized science for strategic missions. The mapping indicates possible applications for new technologies in the priority science targets. However, technology development should remain open to new technology ideas that we can apply outside the strategic mission lines, such as the Explorer Program and Missions of Opportunity.

Heliophysics Technology: Instrument Development

It is recommended that increased investment in instrument development and related technologies be made through the SR&T and LCAS program elements. Key areas that would potentially benefit missions in development and the science Targets prioritized in this roadmap would include improving detectors in functionality, components, and design. Desirable improvements would include, but are not limited to the following:

	STP #4	STP #5	STP #6	STP #7	LWS #3	LWS #4	LWS #5	LWS #6	LWS #7	LWS #8	LWS #9
Rapid application of new technologies with reduced noise and insensitivity to heat and radiation for missions approaching the Sun			•				•	•			
Improved sensitivity to UV and EUV for solar and auroral remote sensing (LWS #7, #9), but also solar blind/UV blind ENA sensors for magnetosphere and heliosphere imaging									•	•	•
Adaptability of geometric factor, fast pulse-height analysis and radiation hardness to increase operability during radiation events or in radiation belts			•		•	•	•	•	•		•
Improved in situ particle optics with larger apertures and/or improved identification for in situ composition analysis	•	•	•	•	•		•	•	•		
Larger array CMOS detectors for increased spatial resolution and sensitivity to short-wavelength remote sensing		•	•	•			•			•	•
Increased spectral resolution systems and lifetimes for IR, FUV, and EUV for solar and planetary upper atmosphere spectroscopy		•	•	•					•	•	
Improved polarization measurements, more effective IR detector cooling devices, higher reflectivity mirrors, and diffraction-limited optics for EUV for space climate and solar remote sensing			•	•					•	•	

Cross-Discipline Technology That Enable Future Mission Concepts

Several unresolved but high-priority science questions cannot be reasonably addressed with currently existing technology or resources. This drives the associated science missions beyond the recommended science queue. Before progress can be made, investments in critical technologies must be made that enable those missions to become feasible. This investment should be made in the near term in order that the technology can mature to the point that the associated science missions are enabled in a timely fashion. Example technologies are listed below:

- In-space propulsion—solar sails, stable solar electric propulsion for reaching and maintaining vantage points in space.
- Improved power sources for near-Sun and deep-space missions.
- Radioisotope supply for near-Sun or deep-space power generation.
- High-rate, long-distance optical communications for increased data rate of deep space or fleet missions.

New technologies that should be rapidly employed by Heliophysics, but also would equally benefit the other SMD science divisions include, e.g., onboard data compression, fault-tolerant computing, miniaturized electronics and power supplies, low-power sensors, and application-specific integrated circuits. The common thread of these technologies is that they help the Agency accommodating the best possible scientific sensor solutions on upcoming missions. Thus, it is imperative that Heliophysics does not fall behind in applying them.

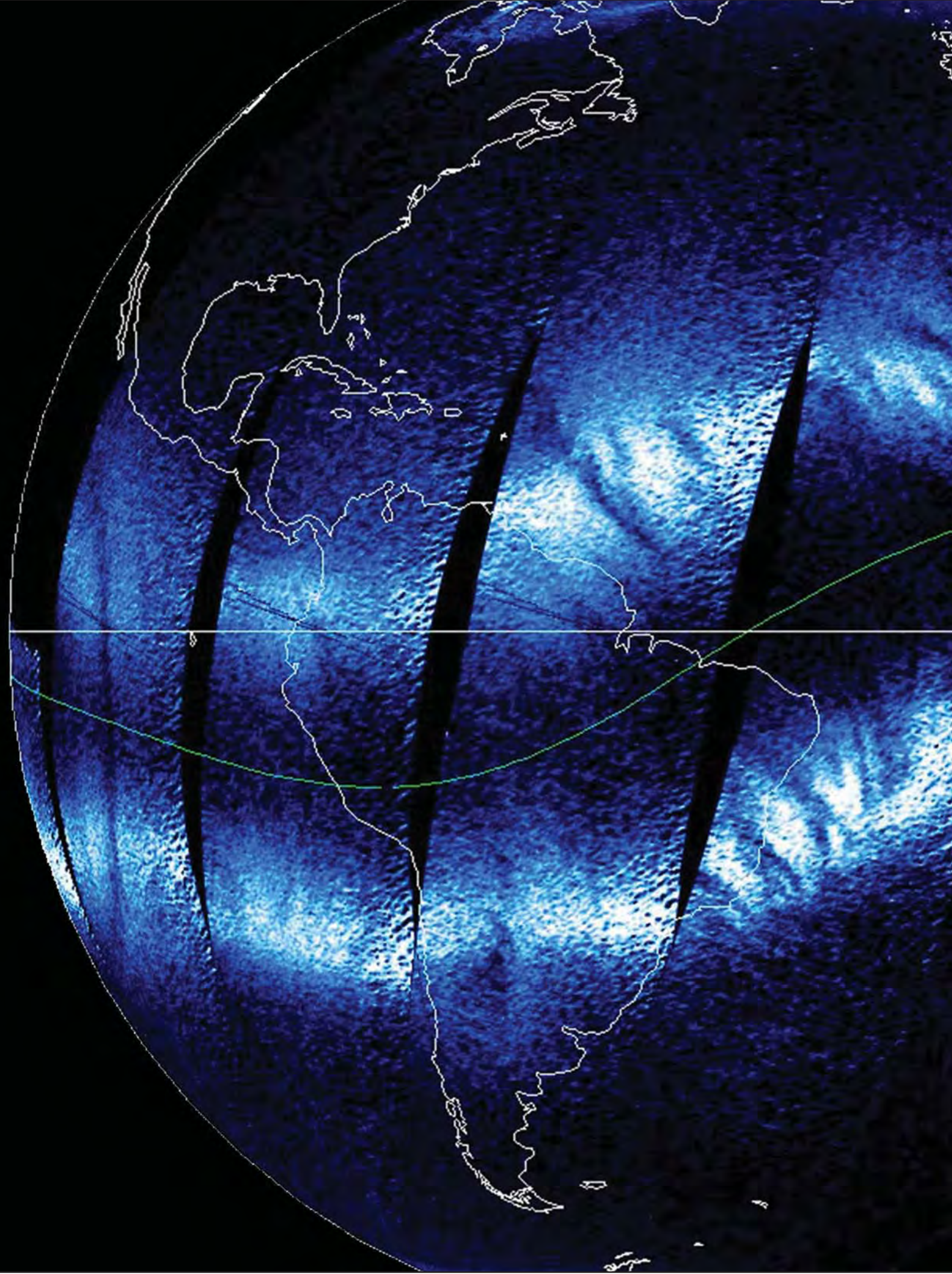
The Heliophysics Division is not able to alone shoulder a number of major developments that have immediate applications across NASA's Science Divisions, other NASA Directorates, or other national agencies.

- Low-cost launch platforms and spacecraft busses.
- Lightweight structures and nanotube technology.
- Replacement for a Delta II launch capability.

Cross-Discipline Technology: Advanced Information Technology

We look forward to a continuing exponential growth in science data resources returned from our space missions. This explosion, in terms of volume, complexity, and multiplicity of sources will call for new and innovative analysis paradigms to transform that data into knowledge and understanding. Advances in computer science and technology afford vital opportunities to deal with this challenging new environment and enhance science productivity. It is recommended that increased investments be made in the area of Heliophysics informatics to include:

- Computational methods and algorithms for multidimensional data analysis and visualization.
- Numerical laboratories for modeling and simulating physical processes and effects.
- “Science Discovery Infrastructure” consisting of robust tool sets for mining huge volumes of multidimensional data from all observatories and models, and extracting and cataloging features and events.
- Onboard science autonomy for sensor webs drawing from Heliophysics observatories.





Chapter 4

PRIORITY SCIENCE TARGET DESCRIPTIONS

In recent years the nature of scientific research in general has been evolving toward a greater emphasis on multidisciplinary research. For Heliophysics, we are on the cusp of a significant shift toward an integrated framework of understanding of the Heliophysics system. System science invites and encourages exploratory data analysis, looking for unexpected linkages that are beyond what one might hypothesize in advance. At the same time continued detailed scientific research in the Cartesian sense is absolutely required to deepen our understanding of the fundamental physical processes.

Both detailed in-depth and inductive approaches to science are foundational to the Heliophysics strategy. The first is evident in the structure of the science flowdown leading to science targets designed to reveal the fundamental workings of the system. The incorporation of new Target missions into the Heliophysics System Observatory and the synthesis and modeling provided by the Supporting Research Program elements enables comprehension of the whole.

This Chapter provides science background for the highest priority science Targets introduced in Chapter 3 and the vision of the heliophysics discipline for the future. A science queue is presented that illustrates the anticipated launch dates of the STP, LWS and Explorer missions, including the missions addressing the highest priority science targets. Chosen to breakthrough present blockages in our knowledge, their eventual impact will be a significant advance of understanding. They are an element of the full program of exploration, observation, theory, modeling and simulation which are critical for the development of our knowledge of the past and for extending what is learned to deal with the present and predict the future.

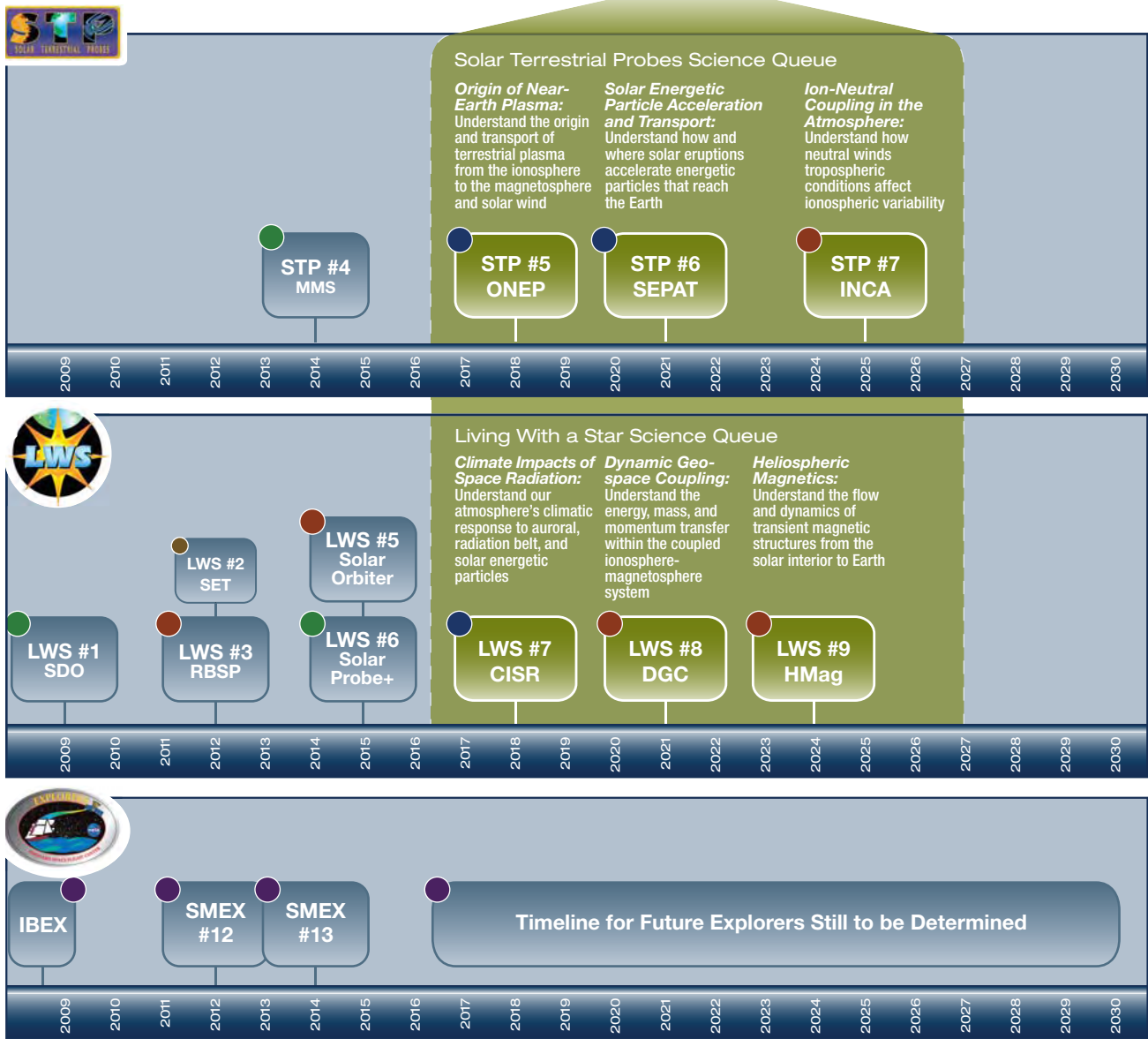
Science Prioritization and the Science Queue

For the first time, we recommend a new, flexible Heliophysics research strategy based on prioritized science objectives. The science queue consists of science Targets that at this point in their development do not have fixed point designs as their implementation strategies. These priority science targets should at a later date be implemented through resources of the strategic mission lines in Heliophysics.

By evaluating both the science and implementation factors, the Roadmap team has associated the highest priority science Targets with cost categories i.e., light, small, medium, and large and placed them into a science queue in either the Solar Terrestrial Probes or the Living with a Star mission lines consistent with the goals of each mission line and the science objective. The timing of the projects was based on the required launch frequency and the FY09 Presidents budget with a 1.0% inflation beyond the 5-year horizon of the budget. Besides the Science Queue, the team identified one high-priority science target for a potential International Partnership, and identified other existing International Partnership opportunities. All science targets are described in this chapter to the extent that the Science Queue warrants, i.e. without prescribing implementation or procurement requirements.

The graphic indicates launch dates for strategic and Explorer missions as presently understood. The missions in development (grey boxes) and the new science Targets (purple boxes) are marked with a colored dot indicating the mission cost class. The boxes are centered on the launch date. The bottom panel lists potential international and intra-NASA partnership opportunities.

Recommended Science Queue



Cost Definitions for Missions:

- Nominal
- Light: <\$250M
- Small: \$250M–\$500M
- Medium: \$500M–\$750M
- Large: \$750M–\$1B

Per NPR 7120.5 D

Potential International Partnerships

- SOLAR-C (JAXA)
- ORBITALS (CSA)
- Cross-Scale/Scope (ESA/JAXA)
- Interstellar Probe

Color indicates NASA contribution not reflected in roadmap budgeting—would require additional resources

Intra-NASA Partnerships

- JUNO
- Mars Atmosphere and Volatile Evolution (MAVEN)
- Mars Science Laboratory (MSL)
- Lunar Reconnaissance Orbiter (LRO)
- Lunar Atmosphere and Dust Environment Explorer (LADEE)

No contribution of funds anticipated



STP #5

Origins of Near-Earth Plasma (ONEP)

Science Mission Objectives

Determine the dissipation processes that heat ionospheric plasmas and the coupling processes that affect planetary ionospheric scale heights.

Science Rationale Summary

The STP #5 science Target ONEP follows from the Fundamental Processes Investigation: How are planetary thermal plasmas accelerated and transported? It is also related to the Societal Relevance Investigation: How do the magnetosphere and the ionosphere-thermosphere systems interact with each other? Understanding planetary plasma acceleration and transport processes is fundamental in determining how planetary ionospheres can contribute to magnetospheric plasma populations. Additionally, some of the ionospheric plasma can ultimately escape into the solar wind. Loss of ionospheric plasma also results in atmospheric loss, since the ionosphere is created through ionization of the neutral atmosphere. In addition, plasma of ionospheric origin often consists of heavier ions, such as atomic oxygen ions. The increased mass density can change the characteristics of the magnetospheric plasma, affecting processes such as reconnection.

To assess how ionospheric plasma is distributed throughout the magnetosphere requires knowledge of how the ions are energized as they escape from the Earth's gravitational potential well. Oxygen ions, for example, must be accelerated and heated to energies much higher than typical ionospheric temperatures to escape, whereas protons can escape relatively easily. At the same time, since the heavier ions tend to have lower velocities, they are more likely to be affected by other processes such as convection, and the final disposition of these ions requires detailed knowledge of their energy distribution as they leave the ionosphere.

The fundamental process of planetary ion outflow has particularly important implications for life on Earth, not only in the study of atmospheric loss, but also in the understanding of geomagnetic storms, their magnitude, and duration. We must better understand the nonlinear processes and feedback that enhance or moderate electrical currents in the magnetosphere to predict storm strength and subsequent societal effects. Ionospheric plasma is a major contributor to the plasma pressure and currents throughout the magnetosphere during these storms. Because the magnitude of ion outflow is related to the storm strength, but also contributes to the storm strength, the interchange of mass and energy between the ionosphere and magnetosphere constitutes the largest nonlinear system in geospace.

Example questions that could be answered with this science Target are:

- What are the sources of energy that drive ionospheric outflows?
- How are these energy sources partitioned as a function of altitude and location, e.g., the auroral oval versus the dayside cusp?
- Where do the different energy sources deposit their energy?
- How does the neutral atmosphere respond to the energy deposition?
- Does variability in winds, etc., within the neutral atmosphere affect the ionospheric response to the energy sources?
- To what degree do feedback and saturation processes control the outflow of plasma?
- What feedback is there on the magnetospheric drivers of the outflows?

This science Target is primarily relevant to Decadal Survey Challenges numbers 3–5:

Challenge 3: Understanding the space environments of Earth and other solar system bodies and their dynamical response to external and internal influences.

Challenge 4: Understanding the basic physical principles manifest in processes observed in solar and space plasmas.

Challenge 5: Developing a near-real-time predictive capability for understanding and quantifying the impact on human activities of dynamical processes at the Sun, in the interplanetary medium, and in Earth's magnetosphere and ionosphere.

This science will address components of Decadal Survey moderate missions #9: Stereo Magnetospheric Imager and #5.

Mapping to RFA, Decadal Challenges, and Decadal Missions

This investigation primarily addresses research focus areas F2 and F3, which are (F2) to understand the plasma processes that accelerate and transport particles and (F3) to understand the ion-neutral interactions that couple planetary ionospheres to their upper atmospheres and solar and stellar winds to the ambient neutrals.

Measurements

- Ion and neutral composition - thermal energies
- Ion and neutral flow velocities
- Ion energy and pitch angle distribution - up to 20 keV
- Electron energy and pitch angle distribution - up to 20 keV
- Magnetic fields DC - 1 kHz
- Electric fields DC - 1kHz
- Plasma density, electron temperature

Note that this is not a prioritized or complete list.

Enhancing Technologies

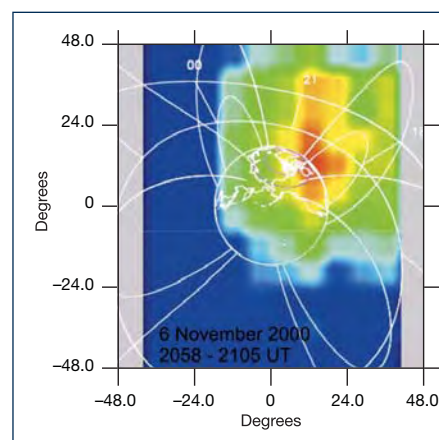
Technology investments that are likely to enhance the science return of this mission include:

- Low mass/power neutral mass spectrometers.
- Spacecraft potential control for measurement of low-energy ions.
- Enhanced ion measurement capabilities for energies <10 eV.
- Spectrographic imaging telescopes for imaging upwelling ion distributions.

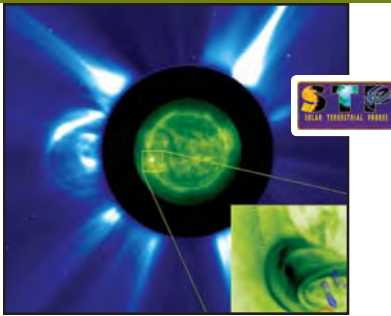
Note that this is not a prioritized or complete list.

Enhancing Pre-mission R&A Focus Areas

- Multifluid MHD, incorporating mass outflows.
- Dynamic magnetosphere-ionosphere-thermosphere coupling models, including wave, collisional, and particle heating.



Ionospheric plasma outflows as imaged by the IMAGE spacecraft (Fuselier et al., JGR, 2007)



STP #6

Solar Energetic Particle Acceleration and Transport (SEPAT)

Science Mission Objective

To understand how and where solar eruptions accelerate energetic particles that reach Earth.

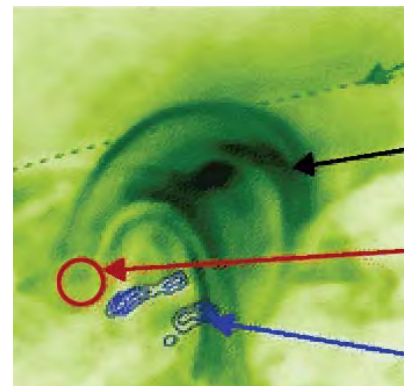
Science Rationale Summary

The STP #6 science target derives from Priority Investigation #2 and #12: “How are charged particles accelerated and transported?” and “How do solar wind disturbances propagate and evolve through the solar system?” These general questions can be investigated in many places within the solar system and many were considered. Several important science questions derive from these general questions, and some are being investigated by STEREO, ACE, Wind, SOHO, Hinode, and RHESSI, while others will be addressed by SDO, MSL, LRO, MMS, Solar Probe+, and RBSP will also provide insight to the general question of particle acceleration and/or transport, but the highest priority science question remaining open was the acceleration due to solar eruptions. Relevance is found in all three of the Objectives for the Division, as well as acute interest and urgency to the Agency’s goal of protecting human and robotic explorers.

Example questions that could be answered with this science Target are:

- How do solar energetic particles reach a wide range of heliospheric longitudes and latitudes and what are the time scales involved?
- How does the distribution of energetic particles evolve in the heliosphere in terms of anisotropy and three-dimensional distribution for electrons, various elements, and charge states?
- What are the physical mechanism and importance of diffusive shock acceleration?
- Where are particles accelerated in and released from solar flares?
- What are the roles of waves, turbulence, and electric fields for particle acceleration?

A superposition of a RHESSI image of gamma-ray and x-ray emissions (contours) with the TRACE satellite extreme UV image (green, negative color table) taken 90 minutes later of the July 23, 2002, solar flare. The superposition clearly shows the large separation between the high-energy emissions. Solar physicists expected to see x rays and gamma rays emerging from the same spots at the base of the flare loops. Apparently, the Sun’s magnetic processes are able to separate the electrons from the ions, sorting them either by mass or electric charge, as they blast them to almost the speed of light. The gamma rays seem to be coming from the feet of the large magnetic field loops, while the x rays come from the feet of the small magnetic loops nested inside the larger ones.



This science Target is primarily relevant to Decadal Survey Challenges numbers 1, 2, and 4, and would build a foundation for 5:

Challenge 1: Understanding the structure and dynamics of the Sun's interior, the generation of solar magnetic fields, the origin of the solar cycle, the causes of solar activity, and the structure and dynamics of the corona.

Challenge 2: Understanding heliospheric structure, the distribution of magnetic fields and matter throughout the solar system, and the interaction of the solar atmosphere with the local interstellar medium.

Challenge 4: Understanding the basic physical principles manifest in processes observed in solar and space plasmas.

Challenge 5: Developing a near-real-time predictive capability for understanding and quantifying the impact on human activities of dynamical processes at the Sun, in the interplanetary medium, and in Earth's magnetosphere and ionosphere.

This science Target will address components of Decadal Survey moderate mission (#4) Multispacecraft Heliospheric Mission and (#8) Solar Wind Sentinels.

Mapping to RFA, Decadal Challenges, and Decadal Missions

Although relevant across the Objectives, this science target primarily addresses the research focus area F2 and, in turn, prepares for solving challenges in J2 and J3. F2 targets our understanding of the plasma processes that accelerate and transport particles; J2 urges the development of the capability to predict the origin, onset, and level of solar activity in order to identify potentially hazardous space weather events and safe intervals, and J3 demands the development of the capability to predict the propagation and evolution of solar disturbances to enable safe travel for human and robotic explorers.

Measurements

Measurements over a range of spatial and temporal scales could include:

- Energetic Particle Intensity, Anisotropy, Composition, and Charge State.
- Solar Radio Observations.
- Solar Wind and Interplanetary Magnetic Field.
- Coronal Soft X-ray Imaging/Timing.

Note that this is not a prioritized or complete list.

Enhancing Technologies

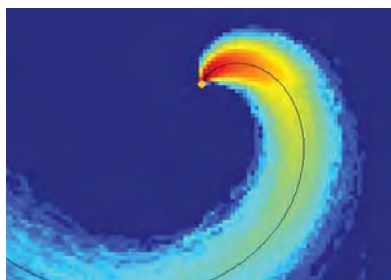
The technology investments that are likely to enhance the science return of this investigation include:

- Rapid application of new technologies with reduced noise and insensitivity to heat and radiation for missions approaching the Sun.
- Adaptability of geometric factor, fast pulse-height analysis and radiation hardness to increase operability during radiation events or in radiation belts.
- Improved in situ particle optics with larger apertures and/or improved identification for in situ composition analysis.
- Larger-array CMOS detectors for increased sensitivity to short-wavelength remote sensing.
- More effective IR detector cooling devices for solar remote sensing.

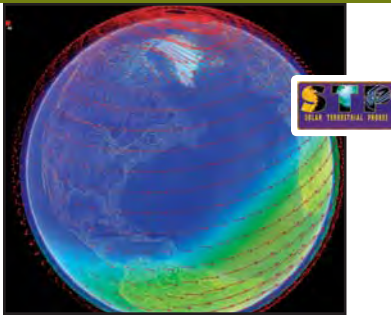
Note that this is not a prioritized or complete list.

Enhancing Pre-mission R&A Focus Areas

Particle transport modeling in the active region/corona/heliosphere system; readdressing particle event analysis measured simultaneously at widely separated spacecraft in the inner heliosphere (e.g., Helios).



Slice through a 3-D simulation of particle transport in the inner heliosphere. The image shows the distribution of 4 MeV protons 24 hours after injection from a point source on the Sun. Image courtesy of W. Droege, J. Kartavykh, G.A. Kovaltsov, and B. Klecker.



STP #7

Ion-Neutral Coupling in the Atmosphere (INCA)

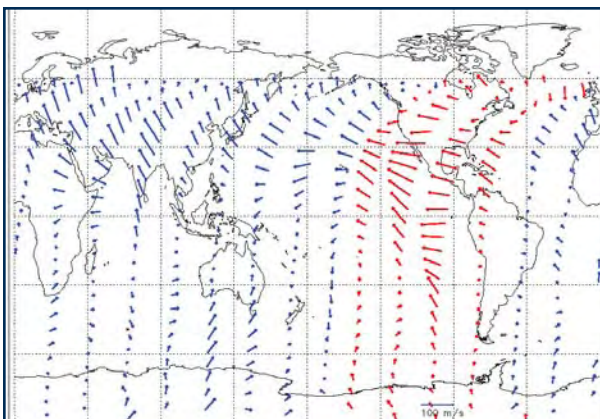
Science Mission Objective

To understand variability in the terrestrial wind dynamo and ionosphere.

Science Rationale Summary

The STP #7 science target INCA derives from the Priority Investigation under Fundamental Processes: What governs the coupling of neutral and ionized species? This general question can be investigated in many places within the solar system and many were considered to address this fundamental process. Several important science questions derive from this general question, some of which are being investigated by planetary missions and the solar mission Hinode and others will be addressed by SDO. The highest priority science question remaining open was the study of the interaction in the weakly ionized plasma of the Earth's atmosphere/ionosphere system. Better understanding of neutral and ionized species under the conditions we find in the ionosphere is applicable to planetary atmospheres, the solar photosphere, and even in the theory of accretion discs in astrophysical systems. But what is it about the atmosphere/ionosphere system that we do not understand that prevents us from a clear understanding of its variability?

We know that important sources of energy that drive the upper atmosphere and ionosphere are externally imposed such as solar EUV, and solar energy imparted to the atmosphere through the solar wind and the magnetosphere during magnetic storms. We have until now not had a good understanding of the dynamics of the system. This lack of knowledge has been recently underscored by observations that clearly show that dynamical disturbances generated in the troposphere modify the wind structure in the upper atmosphere and significantly affect the properties of both the atmosphere and the ionosphere.



Model result showing winds and real-time GPS measurements of TEC (total electron content). Assimilation of GPS transects to form global knowledge of the ionosphere is now regularly performed, while no such assimilation is currently possible due to the total lack of measurements. Thus the science of ion-neutral coupling in geospace is lacking a key component of the system.

Example questions that could be answered with this science target are:

- What are the basic wind fields in the upper atmosphere, especially in the transition region from a mixed to a diffusive regime in the lower thermosphere?
- How do large-scale processes in the lower and middle atmosphere control and influence the upper atmosphere and ionosphere?
- What is the relative importance of coupling due to large-scale waves, wind-driven electrodynamics, composition, and temperature changes in the neutral atmosphere?
- What causes the spatial and temporal variability of the ionosphere and what is the role of the electric field?
- What is the relationship between winds, electric fields, composition, and temperature in understanding the flow of plasma in the ionosphere, especially during magnetic storms?

This science target is primarily relevant to Decadal Survey Challenges numbers 2–4:

Challenge 2: Understanding Heliospheric structure, the distribution of magnetic fields and matter throughout the solar system, and the interaction of the solar atmosphere with the local interstellar medium.

Challenge 3: Understanding the space environments of Earth and other solar system bodies and their dynamical response to external and internal influences.

Challenge 4: Understanding the basic physical principles manifest in processes observed in solar and space plasmas.

This science investigation will address components of Decadal Survey moderate mission #5: GEC and part of moderate mission #2: ITSP of the Geospace Network.

Mapping to RFA, Decadal Challenges, and Decadal Missions

This investigation primarily addresses research focus areas F3 and H2, which are (F3) to understand the role of plasma and neutral interactions in nonlinear coupling of regions throughout the solar system and (H2) to understand changes in the Earth's magnetosphere, ionosphere, and upper atmosphere to enable specification, prediction, and mitigation of their effects.

Measurements

Measurements over a range of spatial and temporal scales could include

- IT winds and temperatures.
- Altitude profiles of neutral and ion properties.
- Lower atmospheric waves.
- DC E fields and ion drifts.
- Knowledge of E-field with neutral wind.
- Knowledge of neutral winds with ion density.
- Gravity waves in the middle atmosphere.
- Range of spatial and temporal scales

Note that this is not a prioritized or complete list.

Enhancing Technologies

The technology investments that are likely to enhance the science return of this investigation include:

- Improved sensitivity to UV and EUV for solar and auroral remote sensing.
- Improved in situ particle optics with larger apertures and/or improved identification for in situ composition analysis.
- Larger array CMOS detectors for increased spatial resolution and sensitivity to short-wavelength remote sensing.
- Increased spectral resolution systems and lifetimes for IR, FUV, and EUV for solar and planetary upper atmosphere spectroscopy.
- Improved polarization measurements, more effective IR detector cooling devices, higher reflectivity mirrors, and diffraction-limited optics for EUV for space climate and solar remote sensing.

Note that this is not a prioritized or complete list.

Enhancing Pre-mission R&A Focus Areas

Additional knowledge concerning the properties of upper atmospheric winds would enhance the design and implementation of INCA. Research should include additional measurements of the winds using rocket-based investigations in LCAS. Modeling and theory is also needed to help us understand the large-scale structure of the wind system.



LWS #7

Climate Impacts of Space Radiation (CISR)

Science Mission Objective

To understand our atmosphere's response to auroral, radiation belt, and solar energetic particles, and the associated effects on nitric oxide and ozone.

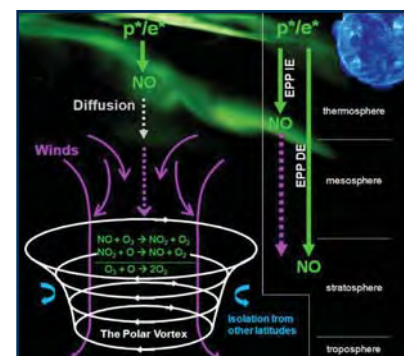
Science Rationale Summary

The LWS #7 science target Climate Impacts of Space Radiation (CISR) derives from Priority Investigation #18 under Societal Relevance: How do long-term variations in solar energy output affect Earth's climate? The solar UV radiation and total solar irradiance side of the question is being addressed by the SORCE/EOS, TIMED, and SDO missions. The solar cycle and secular changes in the middle atmosphere, thermosphere, and ionosphere are being addressed by the TIMED and AIM missions. The remaining highest priority science question is the atmospheric response to energetic particles.

The upper and middle atmosphere are important for climate change studies both as an active participant in modulating climate and as a sensitive (and thus early) indicator of possible changes already underway. Most of these effects are due to anthropogenic changes in atmospheric composition, but solar influences become progressively more important with increasing altitude. Understanding the influence of energetic particle fluxes into the upper atmosphere is motivated especially by their influence on ozone chemistry. There is a dramatic natural variability in the production and transport of nitric oxide (NO) above 100 km in response to particle precipitation during magnetic storms. This contributes to the odd-nitrogen balance of the mesosphere as the NO is transported downward during the winter polar night, which contributes to the catalytic destruction of mesospheric ozone. Higher-energy particles such as from the radiation belts can penetrate directly into the mesosphere, and during intense solar energetic particle events, ionization, and creation of odd-nitrogen can occur even in the stratosphere. These processes have been observed for some events, but there is no systematic understanding of whether the indirect transport mechanism is as important as direct in situ ionization. The global scale climate impacts of the production and transport of these reactive species also remains unknown.

Example questions that could be answered with this science target are:

- What is relative importance of auroral, radiation belt, and solar energetic particle processes for the generation of reactive chemicals and ozone destruction in the middle atmosphere?
- How large are ozone depletions during solar energetic particle events?
- What are the global transport processes for reactive species?
- What is the response of mesospheric and thermospheric state variables to reactive species concentration and distribution?

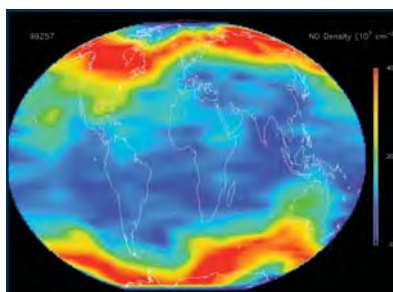


Direct and indirect impact of energetic particles on odd-nitrogen and ozone destruction in the middle atmosphere.

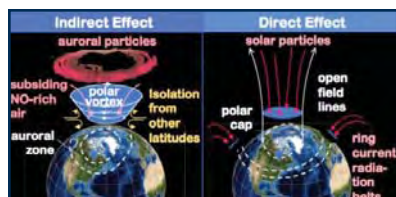
This science target is primarily relevant to Decadal Survey Challenge number 3:

Challenge 3: Understanding the space environments of Earth and other solar system bodies and their dynamical response to external and internal influences.

This science investigation will address some components of Decadal Survey moderate mission #5: GEC, and part of moderate mission #2: ITSP of the Geospace Network.



Global measurement of NO density at 105 km altitude following a geomagnetic storm.



Direct and indirect impact of energetic particles on odd-nitrogen and ozone destruction in the middle atmosphere.

Mapping to RFA, Decadal Challenges, and Decadal Missions

This science target primarily addresses research focus area H3 to understand the role of the Sun and its variability in driving change in the Earth's atmosphere and is closely linked to Priority Investigations #6 and #15: How do coupled middle and upper atmospheres respond to external drivers and to each other and what are the roles of mass and energy flows in the behavior of planetary environments?

Measurements

Measurements over a range of spatial and temporal scales could include

- High-energy particle inputs to the upper atmosphere.
- Auroral particle inputs to the upper atmosphere.
- Reactive chemical distribution, including ozone and various odd-nitrogen compounds.
- Upper- and middle-atmosphere temperature profiles.
- Upper- and middle-atmosphere neutral winds.

Note that this is not a prioritized or complete list.

Enhancing Technologies

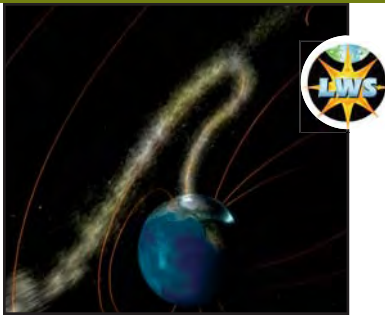
The technology investments that are likely to enhance the science return of this investigation include:

- Improved sensitivity of UV detectors for auroral remote sensing.
- Large-array CMOS detectors for increased spatial resolution and sensitivity to short-wavelength remote sensing.
- Improved in situ particle detectors with larger apertures and/or improved identification for in situ composition analysis.
- Increased spectral resolution systems and lifetimes for IR instruments for solar and planetary upper atmosphere spectroscopy.
- Efficient IR detector cooling devices.
- Reliable and stable doppler interferometry for wind measurements.

Note that this is not a prioritized or complete list.

Enhancing Pre-mission R&A Focus Areas

Improvement of coupled models of mesosphere and lower thermosphere chemistry and dynamics prior to this investigation will greatly enhance the focus of the investigation and enable greater advancement of knowledge of the climate implications of solar variability.



LWS #8

Dynamic Geospace Coupling (DGC)

Science Mission Objective

To understand how magnetospheric dynamics provides energy into the coupled ionosphere-magnetosphere system.

Science Rationale Summary

The LWS #8 science Target DGC derives from the Societal Relevant Science Investigation: How do the magnetosphere and the ionosphere systems interact with each other? And the fundamental questions related to plasma processes that determine how energy and momentum from the solar wind propagate downward through geospace to Earth. Understanding the dominant plasma acceleration and transport processes operative in the Earth's geospace region also has more general applicability. Particle acceleration and particle transport are two of the most fundamental processes in the plasma universe occurring in essentially every region of the heliosphere from the Sun to the heliopause, in the solar wind, in planetary magnetospheres and ionospheres, in cometary tails, and many others. The same processes that have been discovered by Heliophysics missions form a foundation for understanding astrophysical systems.

The question that specifically motivates science target LWS #8 is how mass and energy flow in magnetosphere-ionosphere systems determine and control their coupled behavior. It is in the magnetosphere-ionosphere system where the basic physical processes of particle acceleration and transport have the most direct impact on human activity through space weather impacts on satellite operations, through disruption of electromagnetic signals passing through the ionosphere, and through dramatic reconfigurations of the electrodynamic currents that connect the Earth to the heliosphere through the ionosphere and magnetosphere. The DGC science Target (LWS #8) was specifically formulated to understand how particle acceleration and transport couple the magnetosphere to the ionosphere through the flow of mass and energy.

The next step in answering these questions will be achieved through simultaneous measurement of the dynamics of the ionospheric and magnetospheric auroral regions. Magnetospheric dynamics can be understood through in situ measurements across spatial scales characteristic of global circulation while ionospheric dynamics can be remotely probed through auroral imaging. The aurorae are much more than a passive response to the deposition of energy into the ionosphere by magnetospheric particles and currents. Auroral acceleration and heating change both ionospheric and magnetospheric currents as well as provide ionospheric plasma to the magnetosphere. The nature of these processes, their linked responses to solar wind driving, and the interrelationships between different regions are the key to understanding dynamic geospace coupling.

Example questions that could be answered with this science target are:

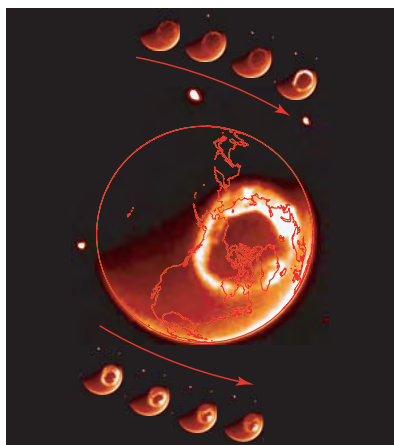
- How do magnetospheric particle and field signatures relate to visible/UV auroral forms?
- To what extent are auroral forms conjugate?
- What magnetospheric parameters control the degree of conjugacy?
- What do nonconjugate auroral forms tell us about the ionospheric control of magnetosphere-ionosphere coupling?
- How does magnetosphere-ionosphere coupling control particle outflow from the auroral regions?
- What are the source of currents that couple the magnetosphere and ionosphere?
- What is the energy input from the magnetosphere to the ionosphere through precipitating particles?
- To what extent do the ionosphere and magnetosphere “drive” the dynamics of the other region?

This science target is primarily relevant to Decadal Survey Challenges numbers 3, 4, and 5:

Challenge 3: Understanding the space environments of Earth and other solar system bodies and their dynamical response to external and internal influences.

Challenge 4: Understanding the basic physical principals manifest in processes observed in solar and space plasmas.

Challenge 5: Developing a near-real-time predictive capability for understanding and quantifying the impact on human activities of dynamical processes at the Sun, in the interplanetary medium, and in Earth's magnetosphere and ionosphere.



Mapping to RFA, Decadal Challenges, and Decadal Missions

This science target primarily falls under research focus areas H2 to understand changes in the Earth's magnetosphere, ionosphere, and upper atmosphere to enable specification, prediction, and mitigation of their effects and F2 to understand the plasma processes that accelerate and transport particles.

Measurements

To understand coupling between the ionosphere and magnetosphere systems it is necessary to make measurements of the dynamics of both. Magnetospheric dynamics are best measured by probes at multiple locations within the system separated spatially on scales that are characteristic of global circulation. This implies in situ measurements of plasma, energetic particles, electric, and magnetic fields at points separated by distances of RE. While ionospheric dynamics can be studied in detail by in situ measurements, another valuable tool is remote sensing through auroral imaging. Global imaging provides systemwide context while high spatial and temporal resolution imaging of more limited regions probe detailed coupling. Simultaneous, conjugate imaging provides critical information on how ionospheric conditions differ in the two hemispheres and what those differences can tell us about magnetospheric coupling—in particular, the flow of particles and currents between different parts of the system.

Enhancing Technologies

The technology investments that are likely to enhance the science return of this science target include: high spatial and temporal auroral imaging in the EUV/FUV wavelengths, electric field instruments with lower spacecraft impact than current systems, low-resource plasma and energetic particle measurements with ion composition, innovative systems to neutralize spacecraft potential, and technologies and processes to reduce cost and risk in multispacecraft missions.

Enhancing Premission R&A Focus Areas

The science return from missions fulfilling science target LWS #8 could be significantly enhanced through advance R&A of data collected from simultaneous measurements of magnetospheric dynamics and auroral processes. Theory and modeling of global electrodynamics, the effects of particle precipitation, and expectations for auroral conjugacy would also provide high value.

Evolution of the aurora during the July 15, 2000, Bastille Day magnetic storm. 1423UT–1512UT



LWS #9

Heliospheric Magnetism (HMag)

Science Mission Objective

To understand the flow and dynamics of transient magnetic structures from the solar interior to Earth.

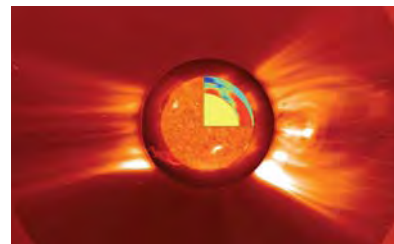
Science Rationale Summary

The LWS #9 science Target derives from two Societal Relevance Investigations: What are the precursors to solar disturbances? and What is the magnetic structure of the Sun-heliosphere system? The ultimate goal is to obtain a physical understanding of the evolution of heliospheric magnetic fields, from their origin deep within the Sun near the tachocline, through subsurface motions of magnetic fields before they appear in the photosphere as sunspots, and into the corona and interplanetary space. After an eruption has occurred, the path of ejecta through the heliosphere is then controlled by the interaction of the large-scale magnetic fields that shape interplanetary space. Several important science questions derive from this general question, and some are being investigated by the solar missions SOHO and STEREO, while others will be addressed by SDO. Solar Orbiter and Solar Probe+ will also provide insight to the general question, but the highest priority science question remaining open was connecting the magnetic field from the solar interior to Earth. Relevance is found in all three of the Objectives for the Division, as well as acute interest to the Agency's goal of protecting human and robotic explorers.

The causes and effects of transient solar activity are a main focus on the path to identifying the precursors and impacts of major solar eruptions. The solar tachocline and convection zone are the origins of strong dynamo magnetic fields. Detailed understanding of magnetic field formation and transport to the visible solar surface is crucial for the identification of triggers of sudden solar activity. Trigger mechanisms may then be linked with the propagation and evolution of existing plasma and fields in the solar corona and inner heliosphere. The synthesis of these elements leads to better physics-based models of space weather. A systematic approach is needed, one that combines the physics of the solar interior with the evolution of the inner heliosphere, ideally from a location that permits observations of the Sun-Earth line.

Example questions that could be answered with this science target are the following:

- Are there precursors to new active regions and CMEs observable beneath the solar surface?
- Are there precursors of solar activity in the surface magnetic and flow fields?
- What is the magnetic field structure of the heliosphere?



A composite image of the Sun that depicts the range of a system-level approach to understanding the connection between plasma in the solar interior and the corona, in this case highlighting SOHO's scientific research. The interior image from MDI illustrates the rivers of plasma discovered flowing under the Sun's surface. The surface image was taken with the EUV Imaging Telescope (EIT) at 304 Å. Both were superimposed on a Large Angle Spectroscopic Coronagraph (LASCO) C2 image, which blocks the Sun so that it can view the corona in visible. The image suggests the range of SOHO's research from the solar interior, to the surface and corona, and out to the solar wind.

This science Target is primarily relevant to Decadal Survey Challenges numbers 1, 4, and 5:

Challenge 1: Understanding the structure and dynamics of the Sun's interior, the generation of solar magnetic fields, the origin of the solar cycle, the causes of solar activity, and the structure and dynamics of the corona.

Challenge 4: Understanding the basic physical principals manifest in processes observed in solar and space plasmas.

Challenge 5: Developing a near-real-time predictive capability for understanding and quantifying the impact on human activities of dynamical processes at the Sun, in the interplanetary medium, and in Earth's magnetosphere and ionosphere

This science investigation will address components of Decadal Survey large mission (#1) Solar Probe, moderate mission (#8) Solar Wind Sentinels, and small mission (#4) Solar Orbiter. It will also complement and extend Solar Dynamics Observatory.

Image of a CME from STEREO-A/
SECCHI's Heliospheric Imager taken
on November 5th 2007

Mapping to RFA, Decadal Challenges, and Decadal Missions

Although it is relevant across the Objectives, this investigation primarily addresses research focus areas F4 and H3, which are (F4) understand the creation and variability of magnetic dynamos (H3) Develop the capability to predict the propagation and evolution of solar disturbances.

Measurements

Measurements over a range of spatial and temporal scales should include:

- Helioseismology and vector magnetic field.
- Heliospheric imager.
- Coronal X ray imaging and spectroscopy.
- In situ solar wind plasma and magnetic field measurements.
- Energetic particle instruments.

Note that this is not a prioritized or complete list.

Enhancing Technologies

The technology investments that are likely to enhance the science return of this investigation include:

- In-space propulsion to maintain the spacecraft at the L-5 Lagrangian point trailing the Earth by 60 degrees.
- Enhanced telemetry compression and a high bandwidth telemetry solution for large data volumes required by helioseismology.

Note that this is not a prioritized or complete list.

Enhancing Pre-mission R&A Focus Areas

- Obtaining improved inversions of solar vector magnetic field measurements in the corona.
- Development of improved energetic particle propagation models that take into account the detailed structure of the heliospheric magnetic field.
- Development of dynamic solar-chromosphere-corona models giving the detailed interconnection between heliospheric magnetic fields and solar-magnetic reconfiguration.
- Development of dynamo models with surface field boundary conditions with solar wind and open magnetic field.



The Vision for the Future...

Heliophysics began with a revolution: at the dawn of the space age, rockets became available that allowed us to journey directly into the new and uncharted realms of Earth's upper atmosphere, the magnetosphere, and the solar wind, and to place observatories into space to discover how the Sun controls these space environments. We discovered the regions and boundaries that separate and protect Earth from the harsh conditions in the solar wind unleashed by the Sun's violent outbursts of magnetic and particle energy. We discovered new forms of radiation that were trapped in the magnetic fields surrounding our home in space. Heliophysics was thus born in a pioneering era of explosive discovery at the dawn of the space age.

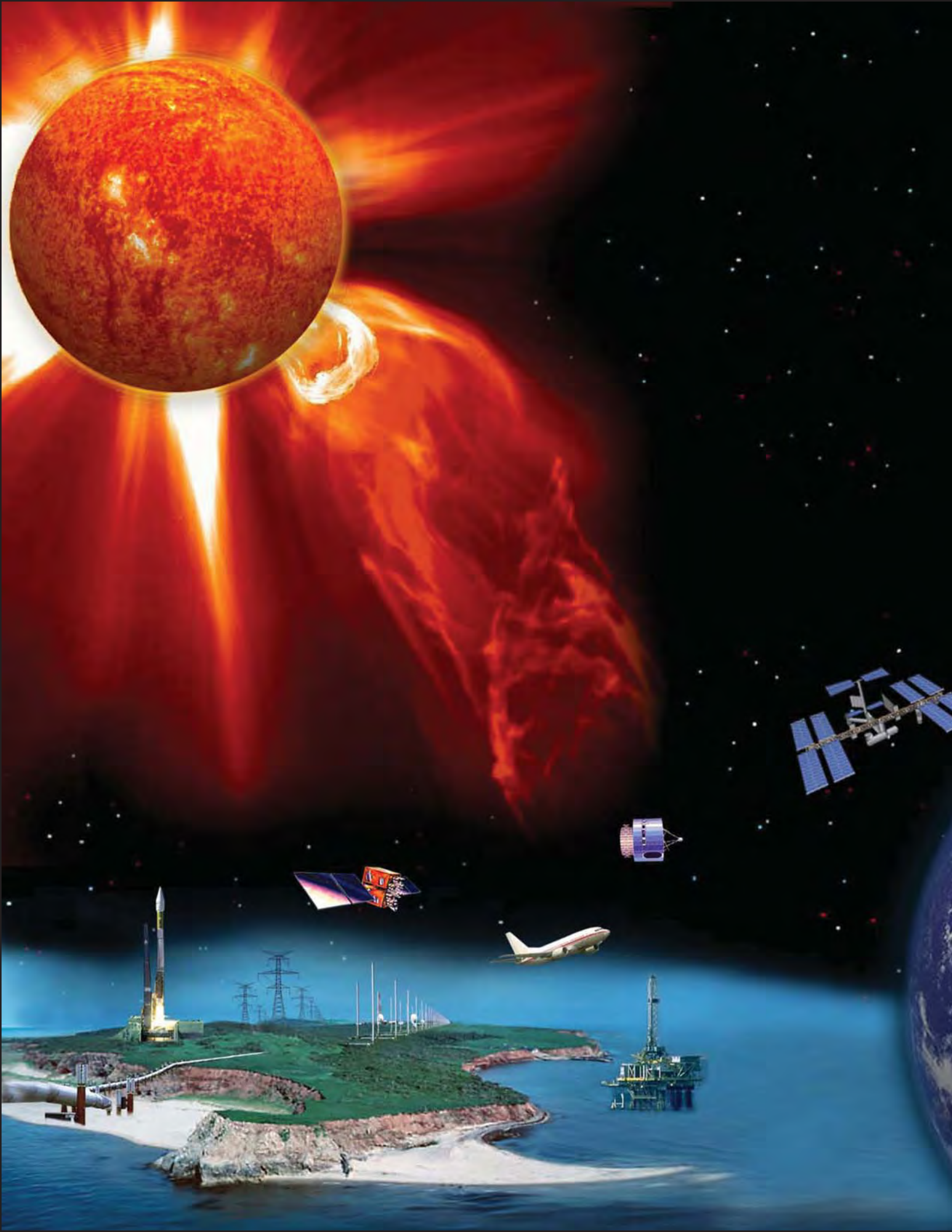
As our field advanced, we realized that we were uncovering a new realm of physics in which matter is organized by magnetic as opposed to gravitational fields. We were able to study this regime in our cosmic backyard (within the solar system) and apply the newly discovered physics of magnetically organized matter throughout the cosmos. We discovered energetic particles and cosmic rays and investigated their source regions and theorized on the cause of galactic and extragalactic cosmic rays. We discovered the sources of magnetic fields within our Sun and are applying our models of the solar dynamo to understand the formation and evolution of other stars. We discovered that the Sun's million-degree corona is the source of the supersonic solar wind which carves out the boundaries that surround our entire solar system and protect it from the harsh radiation of the local interstellar medium. We discovered plasma processes in the outermost reaches of our atmosphere that inform studies of planetary and strongly magnetized plasmas throughout the universe.

We also came to realize that the system was highly complex over large and small scales, from lengths of astronomical units down to the gyration of a single electron. The long range connections between the Sun and the Earth still contain unsolved mysteries due to unidentified processes or complex interdependencies that have yet to be discovered. This complexity means that different components of the system are intertwined, complicating the study of isolated parts. The observational datasets we use are no longer artificially quarantined into scientific subdisciplines. Processes observed in one part of the system are used to correlate to and understand observations made elsewhere.

The need for a broader and more inclusive approach leaves very little wiggle room for loosely conceived ideas. The physics of the system can be triangulated. Holes in understanding can be identified and often tracked back to missing information on small spatial or temporal scales, or a lack of understanding in the governing physical organization. Models of the system are increasingly forced to be global, and if they exclude a physical process, often miss the mark on key observed quantities. The challenge we face is to continue to build upon our understanding of the system as an integrated whole.

In the continued advancement of heliophysics, we aspire to develop models that can be used to predict the space environment. Having entered the digital age, we find that our technological society is increasingly susceptible to the disturbances from the Sun and the particle radiation that impact Earth's magnetic boundaries.

A host of interconnected physical processes, strongly influenced by solar variability, affect the geospace environment, the health and safety of travelers in space, and the habitability of environments on other worlds. Our expanding access to and reliance on space drives us to transform our exploration and discovery of the phenomena of heliophysics into predictive understanding of our home in space and the hazardous space weather to which it responds. Discovery of the fundamental processes that control our space environment relies on direct exploration and observation of these processes in action. Thus, we push the frontiers of heliophysics into new domains in our quest to explore, discover, and understand the interconnections through the hazardous space environment from the Sun to Earth, to the planets, and out to the boundaries of our solar system. As we chart the course of humanity and face mounting challenges to the technological development of society, we are forced with ever-greater urgency to learn to navigate the space environment, to discover the full extent of its influences over our planet and society, and understand its connections throughout the cosmos.



The background of the page is a composite image. On the left side, there is a view of Earth from space, showing the Western Hemisphere with North and South America visible. The Earth's surface is covered in clouds and oceans. On the right side, the background is a dark space filled with numerous stars of varying brightness and colors, including some reddish and bluish hues.

Chapter 5

APPLICATIONS OF HELIOPHYSICS

One of the primary goals for NASA's Heliophysics Division is captured in Objective H – Understand the Nature of our Home in Space. This will be accomplished by studying the Sun, the heliosphere, and planetary environments as elements of a single interconnected system, one that contains dynamic space weather and evolves in response to solar, planetary, and interstellar conditions. Focused research programs addressing specific space environmental hazards will help guide the design and operations of safe and productive missions. At the same time, we will pursue a deeper understanding of the fundamental physical processes that underlie the awesome phenomena of space. Such an understanding will represent not just a grand intellectual accomplishment for our times; it will also provide knowledge and predictive capabilities essential to future human and robotic exploration of space and will serve key societal objectives in important ways.

The payoff in achieving this understanding will be predictions of how human society, technological systems, and the habitability of planets are affected by solar variability. Because it is a complex system, we tend to study individual “disciplines” or “components.” But the Nation's efforts to mitigate space weather effects have placed more urgency on the need to understand the Sun, heliosphere, geospace, and other planetary environments as a single connected system. We make advances by extending the necessarily sparsely-sampled measurements through modeling and theory to achieve system-wide understanding. In time, as the physics-based models mature from the domain of the researcher, they will be transitioned into operational settings where heliophysics becomes the applied science called “space weather,” which has real societal impacts.

Space Weather Impacts on Society

As society becomes increasingly dependent on technologies that are affected by space weather, our vulnerabilities have become more obvious. A report issued in December 2008 by the Space Studies Board of the U.S. National Academies addresses the impacts of space weather events on human technologies. The report, “Severe space weather events—Understanding societal and economic impacts: A workshop report”, estimates that the economic cost of a severe geomagnetic storm could reach US \$1–2 trillion during the first year alone, with recovery times of 4–10 years. These long recovery times could result from severe damage to large power transformers and other hard-to-replace hardware. Such a scenario would result from a storm of the magnitude of one which occurred in September 1859 (Baker, “What Does Space Weather Cost Modern Societies?,” *Space Weather*, 7, S02003, doi:10.1029/2009SW000465, 2009).

Modern society depends heavily on a variety of technologies that are susceptible to the extremes of space weather—severe disturbances of the upper atmosphere and of the near-Earth space environment that are driven by the magnetic activity of the Sun. Strong electrical currents driven in the Earth’s surface during auroral events can disrupt and damage modern electric power grids and may contribute to the corrosion of oil and gas pipelines. Changes in the ionosphere during geomagnetic storms driven by magnetic activity of the Sun interfere with high-frequency radio communications and Global Positioning System navigation. During polar cap absorption events caused by solar protons, radio communications can be severely compromised for commercial airliners on trans-polar crossing routes. Exposure of spacecraft to energetic particles during solar energetic particle events and radiation belt enhancements can cause temporary operational anomalies, damage critical electronics, degrade solar arrays, and blind optical systems such as imagers and star trackers used on commercial and government satellites.

Cooperating Agencies and Organizations

Beyond the science-driven activities in the Heliophysics Division, there are many other groups within NASA who have space weather interests and requirements. The goals and objectives of Heliophysics can directly trace ties to all three science disciplines within NASA’s SMD. There is for example an explicit strategic link to Earth science through our recommended LWS #7 science investigation of solar SEP induced changes in atmospheric chemistry. Ties to Astrophysics lie in fundamental plasma physics and the study of the Sun as a star through helioseismology. The same processes and phenomena that drive space weather in our solar system also shape environments throughout the universe.

Heliophysics also has close ties to NASA’s Exploration Initiative, as well across NASA’s Mission Directorates, examples (in no priority order) include: Aeronautics, where Heliophysics characterizes the Earth’s radiation belt environment needed to design reliable electronic subsystems for use in air and space transportation systems. Exploration Systems relies on Heliophysics to define the radiation and plasma environment to enable exploration of interplanetary space by humans. And Heliophysics develops the knowledge needed to predict solar energetic particle events and surface

charging environments that affect launch vehicles, spacecraft, and surface robotic explorers as well as the safety of humans for Exploration Systems and Space Flight.

Currently, protection of humans in space is an operational activity within the Space Operations Mission Directorate, which supports International Space Station as well as space shuttle flights. The Space Radiation Analysis Group at Johnson Space Center is responsible for ensuring that the radiation exposure received by astronauts remains below established safety limits.

Beyond NASA, but within the US government, inter-agency coordination in space weather activities has been formalized through the Committee on Space Weather, which is hosted by the Office of the Federal Coordinator for Meteorology. This multi-agency organization is Co-Chaired by representatives from NASA, NOAA, DoD, and NSF, and functions as a steering group responsible for tracking the progress of the National Space Weather Program. External constituencies requesting and making use of new knowledge and data from NASA's efforts in Heliophysics include the Federal Aviation Administration (FAA), the Department of Defense (DoD), National Oceanic and Atmospheric Administration (NOAA).

Partnerships with one or more other agencies may be the preferred method for satisfying the national need for observations from L1, measuring solar wind input into geospace. Presently this is accomplished with science satellites making available highly-compressed, relevant measurements in near real-time. This is one of the examples of inter-agency cooperation where "beacons" on NASA spacecraft have provided timely science data to space weather forecasters that is useful for predictions. Successful examples include ACE measurements of interplanetary field conditions from L1; CME alerts arising from SOHO observations; and STEREO beacon images of the "backside" of the Sun. NASA's Heliophysics Division is expected to continue providing this service where relevant.

Some of the commercial ventures impacted by space weather are shown below. The power industry has been aware of the vulnerability of the grid for many decades; and satellite manufacturers and operators take environmental risks into account during the design phase as well as during flight operations. More recently space weather awareness has expanded into industries that include operators of trans-polar aviation routes, as well as precision positioning and navigation companies.

	Real-Time Space Weather Data	Space Environment Specification	Satellite Anomaly Diagnosis	Navigation, Radar, Communication, Transmission Media Error Corrections	Spacecraft Subsystem Technology Transfer	Models of Space Processes for Use in Navigating and Forecasting
Satellite Operations Center	•					
Satellite Operations Directorate	•	•				•
Exploration Systems Directorate		•				•
DSN/TDRSS/Other Communications	•			•		•
NOAA/NWS	•	•				•
FAA	•			•		
DoD	•	•	•	•		
Commercial Satellite Operators	•	•	•			
Power Industry	•					•
Communication Industry	•			•	•	•
Airline Industry	•			•		•
Precision Navigation Industry	•			•		•

International Cooperation

In January 2002, the Interagency Consultative Group established the International Living With a Star (ILWS) program. The IACG consists of the heads of the space science programs of the European Space Agency (ESA), the Japan Aerospace Exploration Agency (JAXA), the National Aeronautics and Space Administration (NASA), and the Russian Aviation and Space Agency (NASA). The charter for ILWS is to “stimulate, strengthen, and coordinate space research to understand the governing processes of the connected Sun-Earth system as an integrated entity. More than 20 contributing organizations are listed at <http://ilws.gsfc.nasa.gov>.

There are also Heliophysics missions in the formulation stage where international collaboration would be of significant benefit. A near-term example is Solar Orbiter in partnership with ESA.

Transition to Operations

The transition of scientific knowledge, usually incorporated in models and simulations, to organizations that could use the knowledge is often a serious challenge in space weather as in most fields. This interface between the scientific community and the operations community responsible for the operation of space systems, air transportation systems, and other operators is at the end of the line for the scientific investigator and upstream for the operators dealing with day-to-day issues. Hence, neither is well equipped to ease the transition. But it is clearly important to reap the investment in space missions and meet the goals in Objective Hs and J.

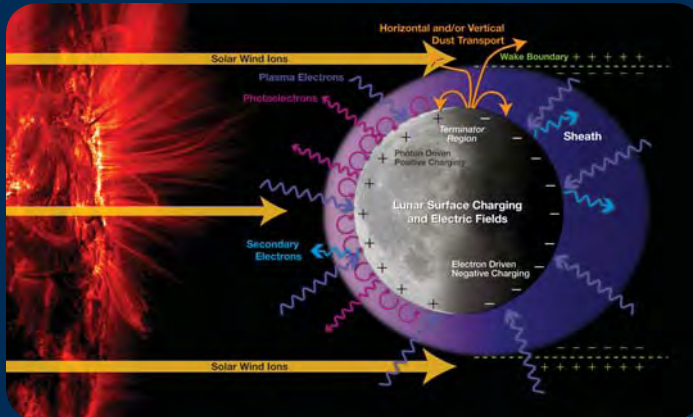
Cross Disciplinary Science

In addition to the contribution of Heliophysics to the solution of practical problems described in previous paragraphs, the contribution to the intellectual pursuit of space science and other cross-disciplinary science is also important. The Heliophysics studies of plasmas apply to solar flares, storms in the Earth’s magnetosphere, and disruptions in laboratory fusion experiments. These are examples of large-scale explosive events driven by the free energy of the magnetic field. The process plays a key role in numerous astrophysical phenomena: star formation, solar flares, and intense aurorae, to name a few. On Earth, magnetic reconnection prevents the efficient production of electricity in controlled fusion reactors, potential sources of electricity for the future.

Heliophysics must deal, by necessity, with a large, complex system that requires the collection and analysis of large multidimensional data sets extending over years of space exploration. The investigators are located across the globe and all need access to the results of space experiments and theory and modeling. Moreover, the very nature of understanding the large, complex coupled system that is Heliophysics, requires advances in techniques to solve coupled, nonlinear mathematical equations. This problem is common to many research areas and is at the forefront of mathematics. Thus, the tools and techniques developed and being developed by this community provide a framework and an example for other disciplines faced with understanding complex phenomena.

Many operating Heliophysics missions have significant international participation:

- Hinode partnership with Japan/JAXA, ISAS, and PPARC.
- STEREO contributions from CNES, Switzerland, DLR, and PPARC, ESA, and Hungary.
- THEMIS contributions from Canada, CNES, DLR, and Austria.
- MMS contributions from recently selected international partners.
- AIM agreement with British Antarctic Survey, Australia.
- TWINS contributions from DLR.
- SOHO partnership with ESA.
- Geotail partnership with Japan/JAXA.
- Cluster partnership with ESA.



The Moon is immersed in a plasma environment—the local cosmos—that is “magnetized.” It is threaded with magnetic fields that are often “frozen” into the plasma, a state of high electrical conductivity that effectively couples the motions of the plasma and the magnetic field. This inherently strong coupling means that the structure and evolution of magnetic fields (of the Sun, of the Earth, and even of the Moon itself) play an essential role in organizing and regulating the local environment of the Moon—the environment to be experienced by our explorers. By working to

understand, and so predict, the variations that occur from day to day, and from region to region, the productivity and overall success of future lunar robotic and manned missions can be significantly enhanced.

The most interesting challenge of the lunar plasma-field environment is that it is alternately dominated by the extended, but variable, outer atmosphere (the “magnetosphere”) of the Earth and by the extended, but highly variable, atmosphere of the Sun (the “heliosphere”). The Moon spends nearly 20% of its orbital period immersed within the Earth’s magnetosphere, which offers some degree of shielding from heliospheric effects; the remaining time is spent exposed to the full effects of the Sun’s radiation and interplanetary fields. Thus, the lunar plasma environment offers unique opportunities to study a variety of fundamental plasma physics processes—processes that have application to many other objects throughout the rest of the Universe.

The heliophysics science associated with the return to the Moon is relevant to RFA J4, “Understand and characterize the space weather effects on and within planetary environments to minimize risk in exploration activities,” and the Decadal Survey Challenge 4 to understand the basic physical principles manifest in processes observed in solar and space plasmas.

In February 2007, a group of approximately 20 experts on solar and space physics met as part of a workshop at the Fiesta Inn Resort conference facilities in Tempe, Arizona. At this workshop, sponsored by the NASA Advisory Council (NAC) and its Science Subcommittees, input from the scientific community regarding recommendations for science associated with the return to the Moon was presented, discussed, and distilled into a series of recommended scientific objectives, each with specific science goals and benefits, and implementation considerations. Those objectives are articulated in a report called “Heliophysics Science and the Moon” (NP-2007-07-80-MSFC, Pub 8-40716). In 2008, the NAC commissioned the Lunar Exploration Analysis Group (LEAG) to develop a priority list of science associated with the return to the Moon. The Moon report team and the Heliophysics Subcommittee assessed the science objectives of the Moon report by sorting them into one of four categories: Compelling science and should be done at the Moon, compelling science but better done elsewhere, interesting science and should be done at the Moon, and interesting science better done elsewhere. The science objectives that are evaluated to be compelling science and should be done at the Moon fell into three distinct areas of research: (1) Investigate plasmas near or on the lunar surface including interaction of plasma and dust grains, (2) observe radio emissions of solar flares and CMEs, and (3) characterize the radiation bombardment on the lunar surface. These three compelling science objectives are consistent with the priority investigations articulated in the roadmap. Achieving them will provide the foundational understanding of the “perilous ocean” which spacefaring spacecraft and crews must traverse in order to reach their destinations within the solar system.

(Note that objectives associated with investigating historical record of the Sun, solar wind, and the local interstellar medium using the lunar regolith were not considered in this evaluation. The planetary science community is assessing this area of research with a similar effort.)





Chapter 6

EDUCATION AND PUBLIC OUTREACH

For nearly 50 years, NASA's journeys into air and space have developed human-kind's understanding of the universe around us, and the planet on which we live. These accomplishments share a common genesis, education. Previous experience has shown us that implementing exciting and compelling NASA science missions are critical to inspiring the next generation of explorers and leaders. Through partnerships with the Agency's mission directorates, other federal agencies, private industry, scientific research, and education organizations, we leverage NASA's unique resources to engage the public, inform teachers, and excite students.



The Science Mission Directorate (SMD) implements NASA's three major education goals in coordination with the NASA Education Office:

- Strengthen NASA and the Nation's future workforce.
- Attract and retain students in science, technology, engineering, and mathematics (STEM) disciplines.
- Engage Americans in NASA's programs.

SMD plays an essential role in NASA's Strategic Education Framework to "inspire, engage, educate and employ." Using programmatic tools and resources, SMD continues to build strategic Education and Public Outreach (E/PO) partnerships to enhance the Nation's formal education system and contribute to the broad public understanding of science, technology, engineering, and mathematics (STEM). SMD's E/PO programs share the results of our mission and research with wide audiences. In addition, E/PO programs promote inclusiveness and provide opportunities for minorities, students with disabilities, and minority universities, and other target groups to compete for and participate in science missions, research, and education programs. The combined emphasis on precollege and preworkforce education, diversity, and increasing the general public's understanding and appreciation of STEM areas encompass all three major education goals.

NASA's Strategic Education Framework emphasizes three main areas of E/PO: Formal Education, Informal Education, and Public Outreach.

- **Formal Education** takes place primarily in the classroom setting involving smaller audiences, more contact time resulting in a deeper understanding of the material. This typically involves a formal curriculum with textbooks, teacher workshops, course work at the K–12, undergraduate, and graduate levels.
- **Informal Education** involves settings outside the classroom such as programs held at museums, libraries, or parks. There is usually a much larger audience, less contact time with participants, and information is broader in scope and is aimed at more general audience.
- **Public Outreach** events are unique opportunities for providing larger audiences with relatively new information that excite interest and stimulate curiosity. Efforts tend to make the information accessible and relevant, and to reach out to people and relate it to their everyday lives.

FORMAL EDUCATION:

Heliophysics Summer School

Heliophysics, as a coherent intellectual discipline, is being taught for the first time through a 3-year summer school series that started in 2007. The school focuses on select fundamental plasma-physical processes that are behind many aspects of space weather, including energetic particle generation and its effects, and addresses the climate systems formed by the solar dynamo and the Earth atmosphere.

The summer school has two principal aims: (1) to educate close to 100 students (selected through a competitive process) and two dozen teachers in Heliophysics as a coherent science through highly interactive seminars and hands-on working groups, and (2) to produce a series of textbooks from which Heliophysics may be taught in the future at universities around the world.

The summer school is sponsored by NASA and the University Corporation for Atmospheric Research Visiting Scientist Programs. The third Heliophysics Summer School will be held in Boulder, CO, July 22–29, 2009.

For more information, see:
<http://www.vsp.ucar.edu/HeliophysicsSummerSchool/>



INFORMAL EDUCATION:

NASA Family Science Night: Changing Perceptions One Family at a Time

Family Science Night is a monthly program for middle school students and their families. The program provides a venue for families to explore the importance of science and technology in their daily lives by engaging in learning activities that change their perception and understanding of science. Family Science Night strives to change the way that students and their families participate in science, within the program and beyond.

The program consists of nine 2-hour sessions held at the Goddard Space Flight Center (GSFC) Visitor Center during the school year from September through May. It covers a wide range of Heliophysics related topics: How Big? How Far? How Old? (size and scale of the universe), Have You Ever Seen the Invisible? (light and spectrum), 'Tis the Seasons (seasons), and Batteries Not Included (solar power and engineering).

The NASA Robert H. Goddard Award for Exceptional Achievement in Outreach was awarded to the NASA/GSFC Family Science Night Team for their contribution to education and public outreach in the local community on September 10, 2008. This program is a partnership between the Solar Dynamics Observatory, the Astrophysics Science Division, and the Rochester Institute of Technology Center for Imaging Science Insight Lab.

For more information, see:
<http://sdo.gsfc.nasa.gov/epo/families/fsn.php>

While there are key differences between formal education, informal education, and public outreach, substantial connections and overlaps exist. The ability to recognize these intersections and take advantage of the opportunities they provide is essential to maximizing the value of E/PO programs and activities.

The Heliophysics Division has made a remarkable impact through the commitment of substantial funds for E/PO programs and activities over the last decade or more. E/PO is an important element of Heliophysics flight and research programs, and moving forward, we envision a more coherent and more integrated set of activities. This reflects the evolution of heliophysical science to a system-wide approach of studying the Sun and its effects throughout the solar system. As a result, the Heliophysics community will continue to contribute to a broad public understanding of the science and its relevance to society. Community participation is vital to the success of the Heliophysics E/PO program.

The Heliophysics Division goal is to ensure a coordinated, balanced, and broad portfolio of activities in formal education, informal education, and public outreach through full and open competition. To achieve this goal, the Heliophysics E/PO program is currently being realigned to maximize limited E/PO funding and resources and to correspond with a new SMD E/PO approach.

Significant opportunities exist to extend the impact of Heliophysics science and related mission activities to engage and inspire students in formal education settings, audiences at informal learning centers, and the general public across the Nation and the world via the press and other communication outlets. Therefore, it is necessary to target four strategic communication objectives:

- Seek opportunities to increase and maintain public awareness of Heliophysics science through activities, materials, and events.
- Engage students and sustain their interest in Heliophysics-related STEM subjects.
- Collaborate with and engage educators to enhance their knowledge of Heliophysics-related subjects and activities.
- Build awareness among students, educators, and the public on the diverse range of career opportunities related to Heliophysics science and missions.



Establishing partnerships between Heliophysics missions and other successful E/PO programs that utilize established infrastructures and leverage existing resources are essential to the development of a dynamic and effective E/PO program with national and international impact. Through these partnerships, Heliophysics E/PO can avoid duplicating efforts, and ensure E/PO funds are invested for highest impact.

In the modern age, space exploration continues to thrill the public with new discoveries that help them build a better understanding of the Sun, near-Earth space, the solar system, and the universe. Heliophysics E/PO will continue to play a leading role as an innovator in the formal education arena (K–12 and postsecondary), in museums and science centers, through high production-value films and rich Web site environments, ensuring that a significant fraction of the U.S. population retains its abiding fascination with space exploration and discovery.

PUBLIC

OUTREACH:

SunWorks Exhibit Blends Science and Art

SunWorks is an imaginative, diverse exhibit of art from artists of all ages and from all around the world whose themes feature the science of Heliophysics. The 24 pieces in the exhibit were selected from over 500 submissions to the SOHO SunWorks art contest that ran for 10 months and ended in March 2006.

The SunWorks exhibit has been displayed at over 14 venues in the United States since its opening at the United Nations in Vienna, Austria, in early 2007. The pieces include a 30-inch aluminum Sun, an exotic solar facemask, a Lego block sun, a stained glass piece, and a blown glass plate that looks amazingly Sun-like. The exhibit's schedule has taken it to museums, universities, and libraries through Colorado and California to Florida, including the Kennedy Space Visitor's Center, and it is still going strong. The show is sponsored by the International Heliophysical Year Education and Public Outreach Program and SOHO, an international mission of cooperation between NASA and the ESA.

For more information, see:

<http://sohowww.nascom.nasa.gov/sunworks/>

Appendices

Appendix A—Prioritization Process



The Roadmap Team developed a new scientific prioritization process that starts out at overarching science goals and leads to a science queue. The science queue offers the flexibility in implementation that is needed to ensure a robust science strategy for the future of Heliophysics.

How Our New Process Establishes a Science Queue

We recommend a new, flexible Heliophysics research strategy with a science-based launch queue. The science Targets in the queue do not have fixed point designs as their implementation strategies. They are simply the recommended science objectives for future missions. These science Targets have been evaluated based on specific factors that determine their science value and associated cost. It is anticipated that this approach will help NASA select and fly the best mission to meet the science objectives within cost. This process is not only a departure from former approaches listing a queue of mission designs, but it establishes a novel

process created by the Roadmap Team that provides the Heliophysics Division with flexibility that enables a more far-reaching, robust science program for the future.

NRC and Agency Goals Guide Roadmap Strategy

The Roadmap's science queue is founded on the NRC's Decadal Survey, and on current NASA strategic objectives. At this time, the Decadal Survey recommendations already date back several (6) years and the predecessor Heliophysics Roadmap 3 full years. New missions have become operational since, or now are under development. New observations and discoveries have been made that have impact on the future directions of our science, and the theoretical foundations of Heliophysics have progressed. The proposed strategy has accounted for recent progress and has the flexibility to accommodate future discoveries.

Science Update and Situational Awareness

We have reviewed and updated the Heliophysics Strategic Objectives and Research Focus Areas that link Heliophysics goals with the 2003 Decadal Survey Integrated Research Strategy and Decadal Challenges (Chapter 1). Chapter 2 summarizes and highlights the major accomplishments. Other changes have occurred recently, namely the increase of launch costs and the loss of Delta II class of launch vehicles, that have been so important for Heliophysics science missions.

Open Science Questions

The Heliophysics Division's Strategic Objectives are parsed into three general areas: Open the Frontier to Space Environment Prediction (Frontier), Understand the Nature of our Home in Space (Home), and Safeguard the Journey of Exploration (Journey). Four RFAs comprise each. From these flow Priority Investigations, a set of 18 more narrowly defined science topics. These topics do not map directly to the RFAs, but are derived from the RFAs and the 2003 Decadal Survey Challenges. The Priority Investigations are further separated into those appropriate for funding through the STP mission line addressing fundamental processes, and the LWS mission line addressing science having societal impact.

The team's analysis of past and recent progress resulted in a comprehensive list of currently OSQs that fall under each of the Priority Investigations. Operating missions and missions now in formulation or development are expected to address a subset of the OSQs as shown in Chapter 3. The remaining OSQs constituted the raw material of the prioritization process.

Science Community Input

The science community has in large number attended and contributed to the 2008 Heliophysics Town Hall meeting, through the submission of mission implementation ideas addressing important Heliophysics problems. These new implementation ideas, along with other implementation strategies of the Decadal Survey, missions published in the 2006 Heliophysics Roadmap, and those suggested by Roadmap Team members provided background for the Roadmap Team deliberations and served as examples of possible implementation concepts for science Targets, called reference missions. Reference missions were identified with a cost category and their implementation readiness. Many of the reference missions have been identified as addressing one or more questions in the list of OSQs.

Evaluation and Prioritization of Science Investigations

Within the 18 Research Focus Targets, the Roadmap Team had the task of ranking investigations that address the OSQs within them. The scientific merit of an investigation is evaluated against five criteria:

- Is the science compelling and urgent?
- Does the science address vital national objectives?
- Would the science transform the knowledge base?
- Does the science have discovery potential?
- Does the science enable exploration?

The implementation factor has been taken into account by analyzing one or more design reference missions as the technical solutions as they are currently known:

- Technical Readiness and Feasibility.
- Launcher Availability.
- Development Cost Category.
- Launch Cadence.

Cost categories are consistent with the guidelines of the NASA Space Flight Program and Project Management Requirements, NPR 7120.5D, where the project life-cycle cost category covering \$250M to \$1B has been divided into three subcategories:

- Light Missions (<\$250M).
- Small Missions (<\$500M).
- Medium Missions (<\$750M).
- Large Missions (<\$1B).

Launch Cadence

The frequency of new missions is critical to the development of our science objectives which encompass, fundamental processes and a study of interconnected physical processes over vast dimensions in both time and space. The resulting system science requires the conduct of investigations that assure progress across the broad frontier of key unresolved science questions. These considerations have led us to recommend a launch frequency model of two to three missions per decade for each of the strategic mission lines STP and LWS, excluding Explorer and LCAS launches.

In a constrained budget scenario, the number of missions that can be launched within a period of time is determined by the size distribution of the missions. A large number of small missions per decade can be launched and operated almost simultaneously, but their scope and their applicability across the subdisciplines within Heliophysics would be very limited. Very few large missions can be launched, but these would operate in isolation if the launch cadence is small so that missions do not survive until the next large mission is being launched. These principles dictated the recommended launch queue and the cost boxes for the science Targets.

Establishing Science Queues for LWS and STP Strategic Lines

The Roadmap Team has combined the science and implementation evaluation factors to identify the six highest priority science targets in cost categories i.e., light, small, medium, and large, and placed them into a science queue in either the STP or the LWS funding lines consistent with the goals of each. The timing of the projects was based on the required launch frequency and the FY 2009 President's budget with 1% inflation rate per year beyond the 5-year horizon of the budget. Besides the Science Queue, the team identified one high-priority science Target for a potential International Partnership, and identified other existing International Partnership opportunities. All science Targets have been described to the extent that the Science Queue warrants, i.e., without prescribing an implementation (Chapters 3 and 4).

Appendix B—Science Traceability Matrix

The scientific goals flowing from the basic documents and the RFAs articulated in the 2006 Heliophysics Roadmap were the foundations for the development of this Roadmap. Discussions at the Community Workshop, review of recent progress in Heliophysics science, and other documents and inputs led to a restatement of the RFAs into 18 science investigations as discussed in Chapter 2 and contained in the blue headers in the spreadsheet in this appendix.

For each of the priority investigations, an analysis of the science needs led to a set of questions at the next level of detail shown as yellow entries in the spreadsheet. At the next level, of refinement a set of science questions referred to as the critical open science questions were identified and shown in white background in the spreadsheet.

For each of the Open Science Questions, an assessment was made of the degree to which they were being addressed by either operating missions in the HSO or expected to be addressed by missions in development.

The operating missions are identified in the column labeled In Flight and science questions to be covered by missions in development are identified in the Development column. A color code of light green means the science question is already part of the Heliophysics flight program.

Many critical science questions remained unaddressed. These were prioritized following Appendix A. The highest priority science targets are shown in column Next Priority. Six of these targets are recommended for implementation in this Roadmap and are colored pink in the spreadsheet. Other science questions still remain unaddressed and are candidates for future missions or perhaps will be addressed with Explorer and LCAS programs or partnerships shown in orange and purple, respectively.

DRAFT 04/21/09
Focus Investigations

Science Investigations	Open Issues/Priority Objectives	In Flight	Development	Next Priority	Future
What are the fundamental physical processes and topologies of magnetic reconnection?	<i>What are the magnetic field topologies for reconnection?</i>				
	Quantify the characteristics of reconnection (i.e. scale sizes, geometries, candidate processes, locations, consequences, and frequencies of occurrence).	HSO			
	Discover the dynamics, scale size, and energy balance of distant magnetotail reconnection and turbulence processes	ARTEMIS			
	<i>What are the fundamental physical processes of reconnection?</i>				
	Inventory the mechanisms leading to reconnection on the Sun. Where are they located? Where are the acceleration regions?	Hinode			
	Understand the microphysics of magnetic reconnection by determining the kinetic processes responsible, especially how reconnection is initiated		MMS		
	Microphysics of reconnection at the Sun: Do the processes differ from those at Earth? What triggers fast reconnection in large flares?				Remaining to be addressed
	<i>How do the large-scale topologies of magnetic reconnection affect microphysical processes, and vice-versa?</i>				Cross Scale (Partnership Opportunity)
How are plasmas and charged particles heated and accelerated?	<i>How are charged particles accelerated and decelerated?</i>				
	Understand the mechanisms and importance of diffusive shock acceleration	HSO			
	Determine how particles are accelerated through magnetic reconfiguration		MMS		
	Catalogue the interaction of energetic particles with the moon and Mars		MSL, LRO		
	Understand the mechanisms and importance of stochastic acceleration		RBSP		
	Determine the importance of seed populations and how they are created		RBSP		
	<i>How are energetic particles transported?</i>				
	Connect the particles producing solar radio bursts back to the corona	RHESSI			
	How and where solar eruptions accelerate the energetic particles that reach Earth			STP #6	
	<i>What is the relative importance of different mechanisms in different environments?</i>				
	Determine acceleration mechanisms for anomalous and galactic cosmic rays-	Voyager IBEX			
	Determine acceleration mechanisms for energetic storm particles in Geospace				Remaining to be addressed
	Determine the acceleration mechanisms for energetic particles in solar flares				Remaining to be addressed

Science Investigations	Open Issues/Priority Objectives	In Flight	Development	Next Priority	Future
How is the solar wind accelerated?	<i>What are the sources of energy for solar wind acceleration?</i>				
	Investigate the interaction between the Sun's magnetic field and the corona	Hinode			
	Relative heating of electrons and ions and nonthermal signatures within the corona	ACE			
	Study processes that accelerate the solar wind and generate coronal mass ejections			CPEXX	
	Reveal the dynamics of the solar chromosphere and transition region			IRIS	
	Measure gradients in energy density in the corona				Remaining to be addressed
	<i>Where does solar wind acceleration occur?</i>				
	Mechanisms of particle acceleration in the low corona and the interplanetary medium	STEREO			
	Distinguish accelerating processes on the Sun			SO	
	Distinguish accelerating processes near the Sun in situ			SP+	
	<i>What is the role of waves and dissipation in solar wind acceleration?</i>				
	Understand the energy dissipation modes that dominate heating				Remaining to be addressed
	Determine the importance of small-scale magnetic reconnection				Remaining to be addressed
How are planetary thermal plasmas accelerated and transported?	<i>How are thermal plasmas accelerated and transported by electromagnetic fields?</i>				
	Determine role of induction fields and wave heating processes	THEMIS	RBSP		
	<i>What determines the composition of upwelling and escaping ionospheric plasma?</i>				
	Determine the drivers of energy deposition	Cluster			
	Determine thermal plasma composition		ePOP		
	Determine the dissipation processes that heat ionospheric plasmas and the coupling processes that affect planetary ionosphere scale-heights			STP #5	
	<i>Does the solar wind affect ionospheric plasma transport at planets such as Mercury, Venus, and Mars?</i>				
	Determine how in situ ionization affects pick up of planetary exospheres, how the interplanetary magnetic field transports ionospheric plasmas, and what mechanisms transfer momentum and energy between the solar wind and planetary ionospheres		Mars Scout		Future Planetary Missions
What governs the coupling of neutral and ionized species?	<i>How are dynamo potentials produced in interaction of atmospheres and magnetized thermal plasmas?</i>				
	Determine what ionospheric current systems are driven by I-T coupling in gas giants		JUNO		
	Variability in the terrestrial wind dynamo and ionosphere			STP #7	
	Energization of terrestrial wind dynamo and the dissipation of that energy				Remaining to be addressed
	<i>What are the consequences of the direct interaction of plasma with planetary, cometary, satellite, and solar atmospheres?</i>				
	Varying Martian atmospheric erosion rates in magnetized regions	Mars Express			
	Solar wind IMF penetration into the Venus ionosphere and effects on mass loss	Venus Express			
	Pickup ionization rate at the Saturnian moons	Cassini			
	Signatures of pickup ions in the solar corona			SP+	
	<i>How do neutral-ion coupling effects govern fundamental processes at the Sun?</i>				
	Reconnection in the partially ionized chromosphere	Hinode			
	First ionization potential fractionation in the low solar atmosphere				Remaining to be addressed

Science Investigations	Open Issues/Priority Objectives	In Flight	Development	Next Priority	Future
How do coupled middle and upper atmospheres respond to external drivers and to each other?	Determine the internal coupling processes within the ITM system and the mediation and control of energy and momentum transfer				
	Chemical pathways to radiation processes and global energy balance	TIMED			
	Response to geomagnetic storms and solar variability	TIMED			
	Neutral winds, disturbance dynamo and equatorial electrojet			STP #7	
	Understand the processes that couple the ITM system to the atmosphere and drive variability				
	Understand the temperature and composition in the ionosphere including those induced by wave and tidal processes			GOLD	
	Understand the global and local electrodynamics of the ITM system in response to geomagnetic dynamics				
	Global characteristics and small-scale physics of plasma irregularities	C/NOFS			
	Global energy characteristics of auroral precipitation				Remaining to be addressed
	Determine the atmospheric response to energetic particles, electromagnetic radiation, and chemical transport				
	Solar spectral irradiance and variability	TIMED SOURCE	SDO		
	Atmospheric response to auroral, radiation belt, and SEPs and transport of reactive chemicals and the effect on ozone				Remaining to be addressed
How do planetary dynamos function and why do they vary so widely across the solar system	Earth	CHAMP	SWARM		Future Earth Science and Planetary Missions
	Mars, Venus, Mercury	Messenger	Mars Scout		
	Gas Giants, astroids, plutoids	Cassini	Pluto, JUNO		
What is the fundamental nature of the solar dynamo and how does it produce the solar cycle?	What is the nature of subsurface flows and the subsurface magnetic field?				
	Relative importance of the two most important regions of dynamo action. Determine the cause of the active longitudes and asymmetric hemispheres	SOHO	SDO		
	Properties of subsurface magnetic fields and characteristics of meridional flows			LWS #9	
	Determine the existence and nature of convective cells				Remaining to be addressed
	Measure the effects of differential rotation				Remaining to be addressed
	Can measurements of subsurface flows and magnetic fields result in understanding the solar activity cycle?				

Science Investigations	Open Issues/Priority Objectives	In Flight	Development	Next Priority	Future
What is the composition of matter fundamental to the formation of habitable planets and life?	<i>What is the composition of particles emanating from the Sun?</i>				
	Solar energetic particle abundances and solar wind CNO charge-state separation	HSO			
	Inventory fractionation processes (e.g., FIP effect)		SDO		
	Determine rare isotopic origins and abundances (3He)				Remaining to be addressed
	<i>What is the composition of planetary magnetospheres and ionospheres?</i>				
	Mercury, Venus, Mars, Uranus, Neptune, Ceres, Vesta encounter	HSO	MSL		
	Pluto, Mercury	Messenger, New Horizons	Bepi Colombo		
	<i>What is the composition of material entering, and interacting with, our solar system? (e.g., interstellar medium, galactic and anomalous cosmic rays)</i>				
	Measure and compare the composition of several samples of matter, including the solar corona, the solar wind, and other interplanetary particle populations, the local interstellar medium, and galactic matter	ACE			
	Determine the relationship of anomalous cosmic rays with the Kuiper belt	Voyager			
	Characterize interstellar dust that penetrate close to the Sun	Cassini, Stardust		SP+	
	Determine the composition of low-energy galactic cosmic rays, the local interstellar plasmas, and interstellar dust populations				Remaining to be addressed
What are the precursors to solar disturbances?	<i>Are there precursors in the surface magnetic & flow fields?</i>				
	Determine which surface field configurations are most likely to flare Temporal changes preceding large flares & filament eruptions	Hinode			
	Magnetic energy storage in the corona from photospheric field extrapolations"	Hinode			
	<i>Are there precursors observable beneath the solar surface?</i>				
	Understand the causes and mechanisms of CME initiation and propagation	SOHO			
	Observe how the Sun's magnetic field is generated and structured in its interior and how stored magnetic energy in the corona is released into the heliosphere		SDO		
	<i>Are there precursors in the chromosphere and corona?</i>				
	Magnetic energy storage in the corona from chromospheric, transition region or coronal field measurements				Remaining to be addressed

Science Investigations	Open Issues/Priority Objectives	In Flight	Development	Next Priority	Future
What is the magnetic structure of the Sun-heliosphere system?	<i>What is the morphology of the heliospheric magnetic field?</i>				
	Determine the origins of solar wind streams and the heliospheric magnetic field	Heliophysics System Observatory	SDO	SO	
	<i>What is the relationship between closed and open flux?</i>				
	Discover whether open flux can disconnect from the Sun in interplanetary space	Wind STEREO			
	Determine whether open/closed regions map to distinctive structures on the Sun and how steady is the boundary between those regions			SP+ SO	
	<i>How does magnetic variation propagate through the heliosphere?</i>				
	Understand the flow and dynamics of transient magnetic structures from the solar interior to Earth			LWS #9	
	Discover how the global magnetic field reverses and why there is a delay between photospheric, coronal, and interplanetary field reversals				Remaining to be addressed
	<i>What is the role of the interstellar magnetic field?</i>				
	Determine the direction of the ISM field and its influence on particle acceleration in the heliosheath	IBEX Voyager			
How do solar wind disturbances propagate and evolve through the solar system?	Determine the strength and influence of the interstellar magnetic field on the shape of the termination shock and heliopause				Remaining to be addressed
	<i>How do solar disturbances erupt and propagate</i>				
	Propagation path and evolution of CMEs to 1 AU, including how these conditions evolve through the solar cycle	Ace Wind			
	Understand the physical processes controlling the heating of the solar corona, the acceleration of the solar wind, and the magnetic release of eruptive activity			Solar Probe +	
	Determine how coronal mass ejections evolve in the inner heliosphere			SO	
	Evolution of source conditions eruptions over the 3-D Sun and inner heliosphere				Remaining to be addressed
	Impact of CMEs and other solar wind disturbances on the global heliosphere				Remaining to be addressed
	<i>How do solar disturbances create particle radiation hazards</i>				
	Investigate particle acceleration and energy release in solar flares	RHESSI			
	Global structure of CMEs and other transients, and how they evolve	STEREO			
How do the heliosphere and the interstellar medium interact?	Sources, acceleration mechanisms, and transport processes of solar energetic particles			SO	
	Discover which magnetic and shock structures in the corona accelerate energetic electrons				Remaining to be addressed
	<i>What are the properties of the termination shock, heliopause, any bow shock, and the conditions of the local interstellar medium?</i>				
	Discover the properties of the termination shock	Voyager			
	Map the global properties of the termination shock and heliosheath.	IBEX			
	Discover the properties of the local interstellar medium, how it changes with time, and determine the implications for our solar system				Interstellar Probe
	Determine whether the termination shock or heliosheath accelerates anomalous cosmic rays				Remaining to be addressed

Science Investigations	Open Issues/Priority Objectives	In Flight	Development	Next Priority	Future
How are mass and energy transferred from the heliosphere to a planetary magnetosphere?	<i>What are the the relative contributions of processes which transfer particles and energy across magnetospheric boundaries</i>				
	Mechanisms controlling the entry and transport of plasma into the magnetosphere	Geotail			
	Three-dimensional studies of plasma structures at the bow shock, magnetopause, dayside cusp, magnetotail and solar wind	Cluster	MMS		
	<i>What is the global response of the magnetosphere and aurora to the solar wind</i>				
	<i>What controls mass and energy transfer at other magnetospheres.</i>				
	Perform initial survey of processes especially mass loading by planetary sputtering, Moons and Rings	Cassini Messenger	JUNO Bepi-Columbo		
What are the transport, acceleration, and loss processes that control the behavior of planetary magnetospheres?	Impact of magnetosphere size, rotation rate, orientation and solar wind IMF on the transfer of mass and energy				Remaining to be addressed
	<i>Establish the global connectivities and causal relationships between processes in different regions of the Earth's magnetosphere</i>	TWINS			
	<i>Determine the mass input and acceleration/loss processes that control the dynamics of the inner magnetosphere.</i>				
	Determine the major acceleration and loss process for the radiation belts.		RBSP CSA-Orbitals JAXA-REG		
	Determine local time and radial dependences of inner magnetosphere processes, including ring current formation/decay and plasmasphere dynamics				Remaining to be addressed
	<i>Determine the processes that control mass and energy storage, conversion and release in the magnetotail</i>				
	Small-scale evolution and dynamics of plasmashet structures, at ~19 RE	Cluster			
	Substorm initiation location	THEMIS			
	Radial and longitudinal plasma sheet dynamics, small and large-scale				Remaining to be addressed
	Role of ionospheric plasma in magnetotail dynamics/spatial and temporal dependence				Remaining to be addressed
	<i>What are the processes that control the dynamics of the aurora?</i>				
	Relate the aurora to magnetospheric drivers.	THEMIS			
	Relationship of Alfvén and electrostatic acceleration mechanisms and how they evolve		LWS #8		
	Characterize signatures of auroral types and identify acceleration regions and acceleration processes				Remaining to be addressed
	Determine whether auroral conjugacy reflects the magnetic configuration of the Earth's magnetosphere as it responds to external drivers				Remaining to be addressed
What is responsible for the dramatic variability of the Ionosphere-Thermosphere-Mesosphere region?	<i>Discover the connections between spatial and temporal scales in the Ionosphere-Thermosphere system</i>				
	Energy transfer, redistribution and radiative transport effects driven by minor constituent chemistry	AIM			
	Understand the global scale response of the Earth's thermosphere and ionosphere		GOLD		
	Multipoint low altitude in situ properties				Remaining to be addressed
	<i>Determine the seasonal dynamics of the Ionosphere-Thermosphere system driven by lower atmosphere processes.</i>				
	Discover how winds and the composition of the upper atmosphere drive the electrical fields and chemical reactions that control the Earth's ionosphere			NICE	
	<i>Understand the electrodynamics that couple the magnetosphere and ionosphere-thermosphere.</i>				Remaining to be addressed

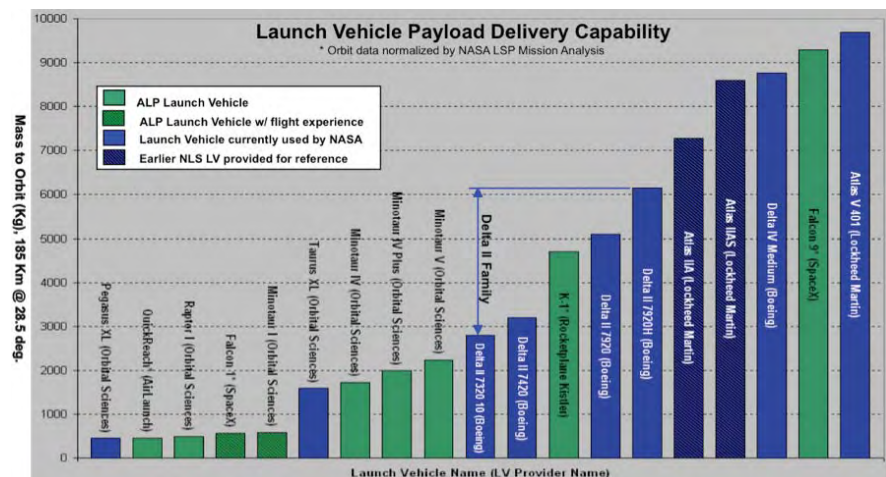
Science Investigations	Open Issues/Priority Objectives	In Flight	Development	Next Priority	Future
How do the magnetosphere and the ionosphere-thermosphere systems interact with each other?	<i>How does energy and momentum from the solar wind propagate downward through geospace to Earth?</i>				
	Magnetospheric storage and release of solar wind energy (SMC vs load/unload)	THEMIS			
	Understand how magnetospheric dynamics provides energy into the coupled thermosphere-ionosphere-magnetosphere system.			LWS #8	
	Interaction/competition of solar wind electric fields and internal magnetic fields				Remaining to be addressed
	High speed solar wind streams effects on the I-T-M system magnetospheric, solar wind, solar radiation energy inputs into lower atmosphere and its response				Remaining to be addressed
	<i>How does energy, mass and momentum propagate upward through geospace?</i>				
	Lower-atmospheric forcing of ionosphere-thermosphere system			NICE	
	Poleward transport of ionospheric plasma energizing magnetic storms				Remaining to be addressed
	Temporal/spatial distribution of ion outflow				Remaining to be addressed
	Dependence of heating rates/outflow on scale size of magnetospheric input, solar flux				Remaining to be addressed
How do long-term variations in solar energy output affect Earth's climate?	<i>Measure the total solar irradiance and solar spectral irradiance as a function of wavelength and solar cycle</i>				
	Solar Ultraviolet Spectral Variation and Total solar irradiance Variation	SORCE	GLORY		
	Solar X-ray and EUV Spectral Variation	SOHO, TIMED	SDO		
	<i>Quantify solar cycle and secular change in the middle atmosphere, thermosphere, and ionosphere</i>				
	Response of mesosphere-lower thermosphere to solar cycle and global change	TIMED			
	Determine why polar mesospheric clouds form and vary	AIM			
	Determine the depth of penetration of solar variability effects through the middle atmosphere and how mechanisms of transmission of middle atmosphere variations transfer to the troposphere				Remaining to be addressed
	<i>Determine the atmospheric response to energetic particles, electromagnetic radiation, and chemical transport</i>				
	Understand our atmosphere's response to auroral, radiation belt, and solar energetic particles, and the associated effects on ozone			LWS #7	
	<i>Understand whether the solar modulation of galactic cosmic rays affect cloud nucleation processes</i>				
	Determine whether cloud nucleation processes are affected by GCRs and quantify the solar/secular changes in albedo, if any				Remaining to be addressed

Appendix C—Cost Control Concepts and Recommendations

This Roadmap recommends that the science imperatives of Heliophysics be addressed with cost capped missions. To implement these missions in the time-frame of the roadmap and to meet the recommended launch frequency, the serious threat of cost growth must be mediated. This applies to missions presently in pre-phase A as well as any future missions. In recognition of the problems attendant with cost escalation, the Roadmap Team strongly recommends that the following prime cost drivers be addressed in the management and procurement of Heliophysics missions.

Procure what we plan, implement what we procure

- The SMD AO process is used to procure science investigations, not build-to-requirement instrumentation. Thus, this roadmap recommends a plan for priority science investigations, leaving the definition of specific mission architecture to the procurement process. In addition, the roadmap recommends that the implementation of strategic missions, whether center-led or PI mission mode, adhere to the requirements and recommended architectures of the peer-reviewed, selected investigation.



The Alternate Launch Vehicle Payload (ALP) delivery capability showing mass to 185 km orbit with a 28.5° inclination as a function of launch vehicle

Minimize the time interval between mission definition and implementation

- The science queue approach described in this roadmap purposely postpones the definition of the mission architecture as long as possible to minimize requirements creep during the often long period between mission pre-formulation and development.

Complete the architectures of new missions.

- The Roadmap Team strongly recommends that the procurement of all strategic missions compete the mission architecture and design requirements at the time of the science investigation procurement. Mission implementation is then most responsive to the latest science innovations, technology breakthroughs, and budget/launcher cost-benefit trades. Heliophysics has been successful controlling costs on Explorer Program Principal Investigator missions. Strategic missions could be implemented likewise. Other models, for example competitive Science and Technology Definition Teams could be utilized.

Avoid the current disconnect between the technical design of a new mission carried out at the Centers and the procurement of the science package carried out by HQ.

- The introduction of competition in the definition of the mission would allow all elements of the mission including the flight and ground segments be defined and procured as a unit. Mission architectures are established at the outset consistent with expected funding.

Other implementation issues that have been identified as significant cost drivers

- Avoid early optimism in formulation that inevitably leads to over optimistic estimates of cost growth during implementation.
- Invest sufficient time and money in Phase A/B for adequate systems engineering studies to more fully understand the requirements and risks.
- Provide a stable and adequate budget profile to avoid costly reprogramming and schedule delays.
- Avoid requirements creep especially NASA-imposed changes in requirements (without a commensurate reduction in risk).

Appendix D—Launch Vehicle Availability

The launch vehicle options for Heliophysics missions have been reduced over the recent years causing the implementation of many proposed missions to be no longer viable. The launch vehicle problem is punctuated by the phasing-out, for NASA use, of the Delta II launch vehicle line. The decision by DoD to transition to the Evolved Expendable Launch Vehicle (EELV) class vehicle has required NASA to bear the increased share of the infrastructure costs. This has made the Delta II unaffordable for NASA. The Delta II launch vehicle was considered the workhorse in the stable of rockets for Heliophysics missions. Its capability, cost, and reliability matched many of the previous roadmap missions.

The unavailability of the Delta II vehicle prompted an assessment of alternate launch providers. The conclusion is that launch capability has bifurcated. The options are either a launch vehicle with small capacity or the very large EELV class. The graphic below illustrates that the launch capabilities of available vehicles are either half the capacity or 2 to 3 times the capacity provided by the Delta II.

The low capacity vehicles (Pegasus XL, Taurus, Minotaur) will meet the needs of a subset of Heliophysics missions. Specifically missions requiring low-Earth orbits or very small payloads in high-altitude orbits. Missions requiring a larger capacity will be very expensive because of the cost of the EELV.

Other options have been considered to address the limited access to space.

1. Co-Manifesting payloads with other missions requires significant early planning. The risk of schedule delay or changing requirements has historically been a significant impediment to this option.
2. International partnerships have had success in the past and can be a viable option. However, significant coordination and consistent long term commitment is required by all agencies for success.
3. New launch providers in the private sector are being developed. However, this has proven to be a difficult undertaking, proving that access to space is not easy or inexpensive.
4. Restrictions on use of DoD and foreign launch vehicles make those options difficult to acquire (DoD) or not available for acquisition (foreign).

In conclusion, the current near-term launch options for future Heliophysics missions limit the mission capability and frequency of missions. The development of a reliable, low-cost launch option to fill the void left by the Delta II would be of tremendous benefit in supporting the Heliophysics mission of understanding the integrated-coupled system.

Appendix F—Mission Quad Charts

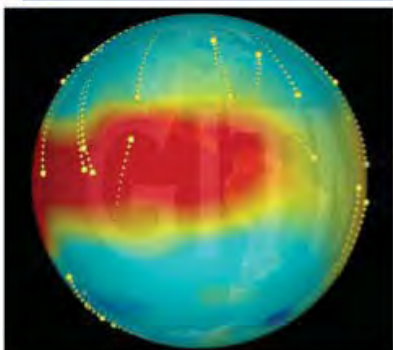
Heliophysics Town Hall 2008

Mission Concepts

- Armada
- Coronal Magnetism, Plasma, and Activity Studies from Space
- Dynamics of the Global Ionosphere-Thermosphere System (DyGITS)
- Electrodynamics Observations with Numerous Satellites (EONS)
- Explorer of the Coupled Ionosphere Thermosphere Electrodynamics (ExCITE)
- Fine-scale Advanced Coronal Transition-region Spectrograph (FACTS)
- Focusing Optics X-ray Solar Imager (FOXSI)
- FUV and EUV Imaging of the Thermosphere and Ionosphere from GEO
- Gamma-Ray Imager/Polarimeter for Solar Flares (GRIPS)
- Geospace Electrodynamics Connections (GEC)
- Geospace Magnetospheric and Ionospheric Neutral Imager (GEMINI)
- Geospace Observer from Large Distance (GOLD)
- Global-scale Observations of the Limb and Disk (GOLD)
- Heliophysical Plasma Physics In Lunar Orbit (HILO)
- High-latitude Dynamic E-Field (HiDEF) Explorer
- Imaging Geospace Electrons Using Thomson Scattering
- In-situ Diagnostics of Universal Plasma Processes
- Interstellar Explorer - An Interstellar Precursor Mission
- IT Constellation
- Lunar Dust Observatory
- Lunar Surface Solar Origins Explorer (LunaSSOX)
- Magnetospheric Constellation (MagCon)
- Magnetospheric Sentinels
- Maneuverable Near-Space Platform
- Neutral Ion Coupling Explorer (NICE)
- Paired Ionosphere-Themosphere Orbiters (PITO)
- PERSEUS - Investigating global heliospheric dynamics from L1
- The Profile Mission
- Radio Observatory for Lunar Sortie Science (ROLSS)
- Reconnection and Microscale Mission
- Solar Activity Farside Investigation (SAFARI)
- Solar Imaging Radio Array (SIRA)
- Solar Magnetized Regions Tomograph (SMART)
- Solar-C Plan A
- Solar-C Plan B
- Solar Polar Imager (aka POLARIS)
- Space Weather Imaging Sentinel (SWIS)
- Stellar Imager (SI)
- Storm-Time Observations by Remote and In Situ Measurements (STORM)
- Thermosphere Ionosphere Global and Regional Imaging in Space and Time (TIGRIST)
- Thermosphere Ionosphere Storm Observatory (TISO)
- Tropical Atmosphere/Ionosphere/Thermosphere (TRAIT) Coupler
- UV Spectro-Coronagraphic Observations of Solar Energetic Particle Related Phenomena



Armada



Mission Implementation Description:

Number of spacecraft: 25-100

Location: The orbit needs to be started around 500 km altitude and is expected to degrade over ~1-2 years. Orbits can be relatively random, from high to low inclination.

Attitude control: Need to make sure that GPS antenna is pointing roughly up and comm antenna is pointing roughly down.

Instrumentation: Dual frequency GPS using civilian bands.

Payload resources: There is significant flexibility in the launching of Armada. This can be done in a staged cluster deployment over a long time period (1-2 years), utilizing free space on various launchers or small launch vehicles.

Measurement Strategy: We will utilize high-resolution GPS measurements to determine the acceleration and drag on each satellite to infer the thermospheric mass density at each satellite location. The dual-frequency measurements will provide slant-path TEC above the satellites. The use of data assimilation within global ionosphere-thermosphere models will allow specification of the global mass density. The time-history of this (within the model) will allow determination of the neutral winds and other quantities.

Science Objectives:

1. Develop an understanding of the global ionospheric, thermospheric, and plasmaspheric dynamics.
2. Understand how high-latitude heating during storms and solar flares affects the global atmospheric structure and dynamics.
3. Understand how forcing from the lower atmosphere affects the thermospheric structure.
4. Understand how waves and the neutral winds redistribute energy throughout the global thermosphere.
5. Understand the global plasmaspheric structure and dynamics during quiet and active time periods.

Associated RFAs:

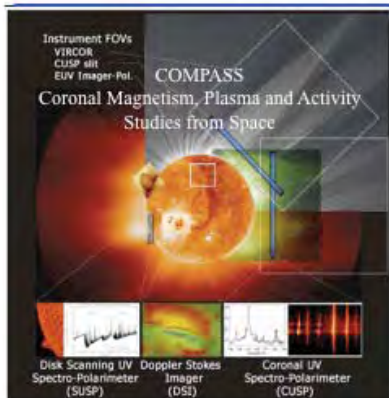
F2.2, F2.4, F3.1, F3.3, F3.5, H2.1, H2.3, H3.2, J1.1, J4.3

Enabling and Enhancing Technology Development:

- No "Enabling" technology required.
- Multiple, identical spacecraft will benefit from streamlined fabrication, test, and management approach.
- Communicating with 100 satellites will involve a distributed array of (low cost) ground-based systems. This can be done with amateur radio groups within universities around the world.
- Determining launches for 100 satellite will involve some planning and clustering of satellites.



Coronal Magnetism, Plasma and Activity Studies from Space



Science Objectives:

- Determine magnetic structure of corona and the connection to magnetic fields in the photosphere via direct measurement
- Understand the nature of changes in the global coronal magnetic field over the solar cycle
- Understand the role of magnetic reconnection in CME formation
- Identify CME shocks in the corona

Associated RFAs:

F1, F2, H1, J2.

Mission Implementation Description:

- Atlas launch vehicle. Two formation flying spacecraft in a halo orbit around Earth-Sun L1. 3-axis stabilized sun-pointing, Solar array powered.
- On-Disk FOV: Scanning UV Spectro-Polarimeter, EUV Imaging-Polarimeter, Doppler Stokes Imager
- Off-Disk FOV: Coronal UV Spectro-polarimeter, Visible & IR Coronagraphic Spectro-polarimeter
- Payload mass: 260 Kg, Power: 1 KW, Telemetry: 900 Kbps/ 78 Gbit/day

Technology Development:

- Formation flying S/C require development of active formation control, relative navigation, and orbit control optimization
- Payload can be accomplished with minimal new technology

Measurement Strategy:

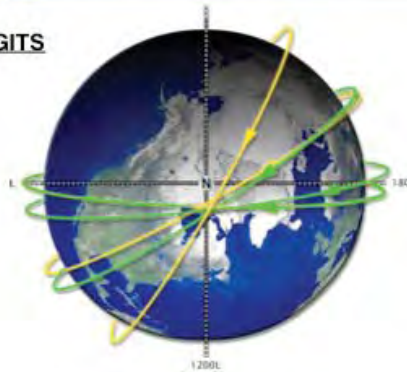
- Provide measurements in the FUV/EUV of the magnetic field in the outer layers of the solar atmosphere (chromosphere, transition region and corona) by recording the Hanle effect, caused by quantum mechanical interference that influences the polarization of spectral lines, as well as the Zeeman effect in different wavelength bands.
- A visible-light magnetograph will provide the magnetic field at the lower boundary of the atmosphere.
- Observe highly ionized spectral lines in the infrared (IR) solar spectrum and White light images in order to get a complementary picture of the field.
- Sample plasma and the embedded magnetic field at a range of heights and temperatures by measurements in multiple spectral lines on and off the solar disk by combining EUV imaging of coronal plasma with FUV spectro-polarimetry.



Dynamics of the Global Ionosphere -Thermosphere System



DyGITS



Science Objectives:

- Characterize dynamics of global I-T system
- Understand how system is driven by lower atmosphere and magnetosphere
 - Quantify total I-T energy budget
 - Model substorms, reconnection, and cusp processes
- Characterize electron and neutral density profiles
- Predict ionospheric irregularities
- Measure Poynting and particle energy fluxes

Associated RFAs:

F, H, J

Mission Implementation Description:

- Polar orbits at ~ 600 - 900 km
- Fixed LT at 12:00 and 21:00 MLT
- Two 3-axis stabilized spacecraft

Technology Development:

- Mini-satellites launched on ESPA ring with DMSP F20
- Smaller, lighter, low power sensors
- Testbed for plug and play technologies

Measurement Strategy:

In-Situ and Remote-Sensing Instruments

- Mini-UV Spectrograph / Imager
- Thermal Plasma Suite
- Magnetometer
- Energetic Particle Detectors
- DORIS Receiver
- GPS Receiver



Electrodynamics Observations with Numerous Satellite



EONS



Science Objective:

To determine when and how the upper atmosphere is driven from below, when and how it is driven from above

Science Questions:

What are the roles of the disturbance dynamo, tidal dynamos and magnetospheric penetration electric fields in determining the global electrodynamics at?

How does the coupling between ion and neutrals affect the structure of the upper atmosphere?

Associated RFAs:

F2, F3, F4, H2, H3, H4, J1, J2, J4

Mission Implementation Description:

6 small-sats in 450 km circular orbits, final configuration separated by 2 hours LT
 3-axis stabilized; eclipse operations
 5 in-situ instruments (TRL-9), 1 remote sensing (TRL 7)
 Payload resources req'd (each sat.): 16kg, 40W, 12kbps

Measurement Strategy: Three Mission Phases

Phase 1: *Pearls on a string* - all 6 satellites are deposited into the same orbital plane at 600 km.

Phase 2: *Slowly phasing* - sequential satellite drops to 450 km after certain months - space satellites out in LT

Phase 3: *Final configuration* - Spread out equally in local time at the same altitude in 6 orbital planes

Enabling and Enhancing Technology Development:

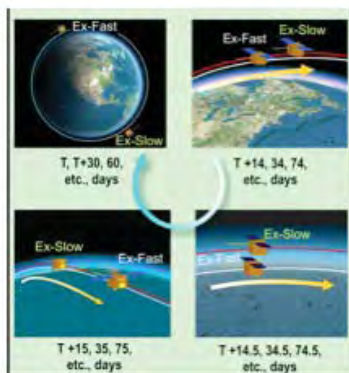
- Small satellite technology with 3-axis stabilization
- Next generation GPS receivers
 - Optimized for small satellites
 - Capable of using Galileo constellation
- Ion thrusters optimized for small satellites would enhance maneuverability/lifetime



Explorer of Coupled Ionosphere Thermosphere Electrodynamics



ExCITE



Science Objectives: In response to magnetospheric and solar inputs the ionosphere and thermosphere respond as a non-linear coupled system. A characteristic of all non-linear systems is the possession of a memory for previous inputs.

Compelling Question

What is the memory time-constant for key ionosphere-thermosphere variables over different spatial scales?

Challenge

Present specification of ALL external drivers to the ionosphere-thermosphere system does not determine the present state of the system

Associated RFAs:

F3, H2, J4

Mission Implementation Description:

- Number of spacecraft 2 (or more incrementally)
- Location LEO 400 KM circular
- Attitude control 3-axis stabilized (1 rev per orbit)
- Number of instruments 4-5
- Type of instrument(s) in-situ/remote ion/neutral drifts, ion/neutral composition energetic particles, magnetic field
- Payload resources required: 115 Kg, 100W, 9kbps per spacecraft

Measurement Strategy:

- Small spacecraft with key measurement capability only.
- Evolution of density and dynamics signatures identified with variable spacing through the same volume.
- Small differences in orbit periods allow time spacing from zero to 1/2-orbit period.
- Simple cold-gas propulsion for drag make-up and orbit period adjustments.
- High inclination provides longitude and local time coverage in less than 2 months.

Enabling and Enhancing Technology Development:

- Uv imaging with high spatial/temporal resolution

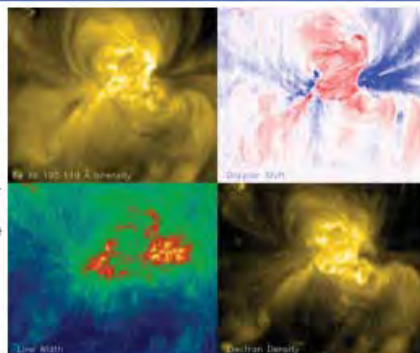


Fine-scale Advanced Coronal Transition-region Spectrograph



FACTS

FACTS will make measurements of the upper solar atmosphere with factor of ~10 better spatial resolution and larger aperture than prior UV instruments.



EIS/Hinode measures intensity, Doppler shift, line width and density.

Science Objectives: determine and characterize the dominant physical processes responsible for the structure, dynamics and evolution of the upper solar atmosphere. These processes drive the global flow of mass/energy in the outer solar atmosphere and space weather events.

Observations: FACTS makes rapid, naturally co-aligned spectroscopic measurements from the photosphere to the corona with 0.1" UV spatial resolution. This combination of temperature coverage and matching spatial resolution has never been achieved before.

Most relevant RFAs:

- F1: Understand magnetic reconnection ... flares, CMEs, ...;
 F2: Understand processes ... that accelerate ... particles;
 H1: Understand causes...solar activity ... that affects earth;
 J2: Develop prediction capability of ... solar activity...;

Mission Implementation Description:

- *Mission: single spacecraft mission, 3 axis stabilized, 24 hour solar viewing for most of the year.
- *FACTS instrument: 0.1" resolution, four channel EUV/Vis (nominal 170-210Å, 500-2000Å, 2000-8000Å) spectrograph, UV/Vis filter imager.
- *EUV spectral imager: 0.1", four channels.
- *estimated payload resources required: ~200-250kg, 120W, 1-5Mbps daily average TM rate, payload TRL 7.

Measurement Strategy:

- *rapid, high spatial resolution, spectra observations.
- *simultaneous, coaligned EUV to Vis spectra.
- *context provided by: coarser resolution rasters, UV/Vis filtergraph, high resolution EUV spectral imager.

Enabling/Enhancing Technology Development:

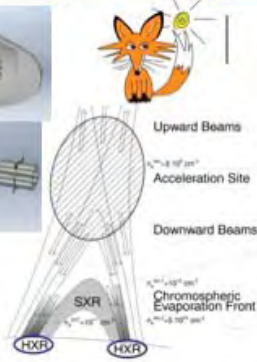
- Light weight mirror technologies and LOS stabilization systems for half meter class optics.
- Efficiency and space/solar-flux durability improvements of EUV optical coatings.
- High speed, small pixel, low noise, EUV and visible sensitive rad hard detectors (especially active pixel sensors and solar blind EUV detectors).
- High quality, EUV ellipsoidal variable line spaced gratings.
- Improvements (cost and performance) of spacecraft ACS and TM (e.g. transmitters, receivers, ground stations, reaction wheels, star trackers, sun sensors).



Focusing Optics X-ray Solar Imager



FOXSI



Science Objectives:

1. Flare Acceleration Region - FOXSI will be able to image where electrons are accelerated, along which field line they travel away from the acceleration site, where they are stopped, and how some electrons escape into interplanetary space.
2. CMEs - High sensitivity HXR observations by FOXSI will enable direct observations of electrons accelerated by CMEs as they travel in the low corona.
3. Radio Emission - FOXSI will allow for the detection HXR emission from electrons that produce coherent radio bursts for the first time.
5. Other targets also include microflares, the Quiet Sun, Solar Axions, and astrophysical sources.

Mission Implementation Description:

- Single 3-axis stabilized spacecraft in Earth orbit.
 - Total weight : 250 kg
 - Power req : 50 W.
 - Sensitivity 100x RHESSI.
- Optics**
- Based on HERO optics (Ramsey et al.)
 - Grazing incidence hard x-ray mirrors.
 - Field of View of 700 x 700 arcsecs.
 - Effective area 150 cm² up to 50 keV (4x RHESSI) or 1 cm² per kg of optics.
 - Spatial resolution of of single shell 7' arcsec FWHM.
- Focal Plane Detectors**
- Si pixel detectors.
 - CZT pixel detectors.
 - based on NeXT mission.

Associated RFAs:

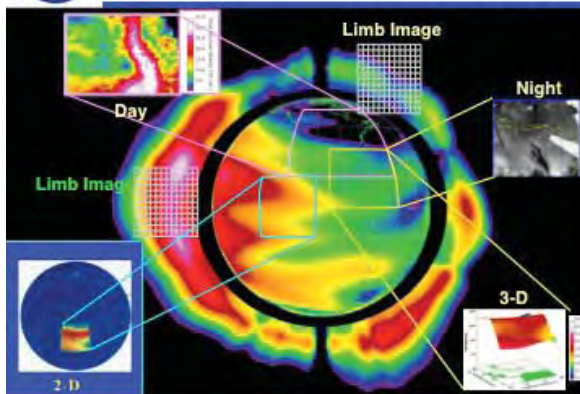
F1, F2, H1

Enabling and Enhancing Technology

1. CZT and Si pixelated detectors - Developed for NeXT, currently are strip detectors with 100 um (Si), 200 um (CZT) strip size. New smaller ASIC will do single pixel readout and
2. HXR Focusing Optics - Based on HERO, new processes in nesting shells and coating deposition will increase the maximum spatial resolution.



FUV and EUV Imaging of the Thermosphere and Ionosphere from GEO



Day & Night Imaging of the Limb & Disk from GEO: O/N₂ & Ionosphere

Science Objectives:

- What is the prompt global-scale ionospheric response to geomagnetic storms?
- What are the extended responses of the thermosphere and the global scale ionosphere to geomagnetic storms?
- How do traveling ionospheric disturbances develop and propagate?
- What affects the day to day variability of the equatorial ionosphere?
- What are the temporal and spatial properties of high latitude upflows and outflows?

Associated RFAs:

F2, F2, H2, H3, J4.

Mission Implementation Description:

- Number of Spacecraft: 1
- Location: Geosynchronous
- Attitude Control: 3-axis stabilized
- Number of Instruments: 1 or 2
- Type of Instrument(s): UV Imagers, mostly TRL9
- Payload Resources Required: 195 lb, offset pointing

Measurement Strategy:

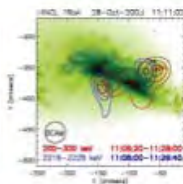
FUV/EUV Imagery at 10 km resolution (best case)

Enabling and Enhancing Technology Developments:

- High performance reflective filters for UV
- High performance microchannel-plate based detector systems
- Newly developed algorithms for inverting the UV radiances to produce neutral and ion densities
- Low cost, frequent access to GEO (presently limited to finding missions of opportunity, which are chiefly on communications satellites)



Gamma-Ray Imager/Polarimeter for Solar Flare



Solar flares accelerate both ions and electrons to high energies. Accelerated ions produce gamma-ray lines through nuclear interactions that reflect the nature and location of their acceleration. Relativistic electrons accelerated in solar flares produce polarized bremsstrahlung emission depending on their angular distribution.

Images from *RHESSI* (e.g., Hurford et al. 2006) indicate that accelerated ions are interacting in localized regions that are spatially shifted from the locations of accelerated-electron interactions.

Mission Implementation Description:

- One spacecraft in a near-equatorial, ~600-km low-Earth orbit
- Three-axis stabilized, mass: 190 kg, power: 340 W, data: 4 GB/day
- Imaging: angular resolution of ~5 to 100s of arcseconds
- Polarization: ~1% minimum detectable polarization at 150–650 keV
- Spectroscopy: 3 keV to 17 MeV, resolution of 1.8 keV at 662 keV
- 3D spatially resolving germanium detectors (3D-GeDs): excellent spectral resolution and spatially locates interactions to $<0.1 \text{ mm}^3$
- Single-grid tungsten Multi-Pitch Rotating Modulator (MPRM): provides a point-response function virtually free from sidelobes
- 20-meter extendable boom separates MPRM and spectrometer for imaging technique, with loose requirements on twist and stability
- Compton-scatter reconstruction techniques used to determine the polarization of incident photons and to provide background rejection

Measurement Strategy:

- Perform a combination of imaging, spectroscopy, and polarimetry of gamma-ray line sources and X-ray sources

GRIPS Fundamental Goal:

Understand energy release at the Sun and its effect on Earth and the solar system by studying particle acceleration associated with solar flares

Science Objectives:

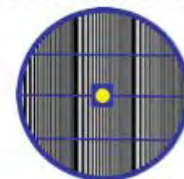
- Determine the spatial distribution of flare-accelerated ions and electrons
- Determine the angular distribution of relativistic electrons
- Study the trapping of relativistic electrons in flare loops
- Determine the accelerated-ion spectrum and associated elemental abundances

Associated RFAs:

F2, H1, J2

Enabling and Enhancing Technology Development:

- Currently funded NASA Low Cost Access to Space balloon version of *GRIPS* will prove these technologies:
 - 3D-GeDs with 0.5-mm strip pitch — detectors with coarser pitch have been built and flown on *NCT* balloon payloads
 - Multi-Pitch Rotating Modulator grid — simple to fabricate and tungsten grids have been used on *RHESSI* and *HEIDI*
 - 20-meter boom — already developed for other space missions



Geospace Electrodynamic Connections



Science Objectives:

- Understand how the ionosphere-upper atmosphere is controlled by magnetosphere forcing
- Determine how the magnetosphere responds to the dynamics of the ionosphere-upper atmosphere

Associated RFAs:

F3, H2, J4

Mission Implementation Description:

- Multiple spacecraft, pearls-on-a-string configuration.
- 185 X 2,000 km; 83° inclination parking orbit; at times, lower perigee to an altitude of ~130 km for ~one week.
- 3-axis stabilized
- 8 identical instruments on each spacecraft
- All *in situ* measuring instruments, TRL-levels 8-9
- Each s/c: ~600 kg dry mass; ~300 watts; ~11Gbits/day

Measurement Strategy:

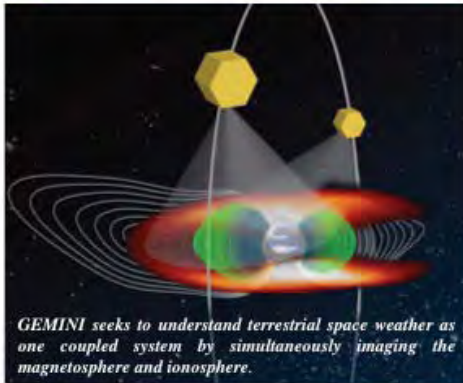
- Measure all plasma-neutral coupling physics parameters
- Sample high latitudes where magnetosphere-ionosphere coupling is greatest
- Variable inter-spacecraft spacing to resolve different scales
- Deep dips to where atmosphere begins to dominate the plasma dynamics

Enabling and Enhancing Technology Development:

Low cost s/c bus.



Geospace Magnetospheric and Ionospheric Neutral Imager



Measurement Strategy:

- Image the 3D distribution and evolution of the two most important populations in the magnetosphere:
 - the ion plasma pressure using energetic neutral atoms (ENA) with sufficient temporal and spatial resolution to retrieve the electrical current system that distorts the magnetic field and that connects through the ionosphere producing the electric field
 - the plasma sphere using extreme ultraviolet (EUV) with sufficient temporal and spatial resolution to retrieve response to the electric field
- Image the ionosphere using
 - multiple wavelengths of far ultraviolet (FUV) to assess auroral energy input and ionospheric-thermospheric composition changes and transport
 - multiple radars to image the plasma flow and electron density profiles in order to estimate the ionospheric electric field and constrain conductance

GEMINI Goal

- Understand the cause and evolution of space weather storms in the magnetosphere-ionosphere system

Science Objectives:

- Visualize the simultaneous 3D evolution of magnetospheric and ionospheric plasma
- Determine the causes and impacts of the explosive growth of plasma pressure in the magnetosphere
- Determine how the global electric field controls transport of plasma throughout the system
- Determine the global variability of the magnetic field in the inner magnetosphere
- Determine the spatial and temporal evolution of the overlap of hot and cold plasma critical for global wave activity

Associated RFAs:

F1, F2, F3, H1, H2, H4, J1, J4

Mission Description

- Two High Altitude Spacecraft in ~8R_E circular near-polar orbit
 - 1 ENA, 1 EUV, 3 FUV cameras per S/C
 - nadir pointing with yaw about nadir
- Ground-based radar network to cover the mid- to high-latitude ionosphere (occasional equatorial coverage preferred)
- 2 year life time

Enabling Technology Development:

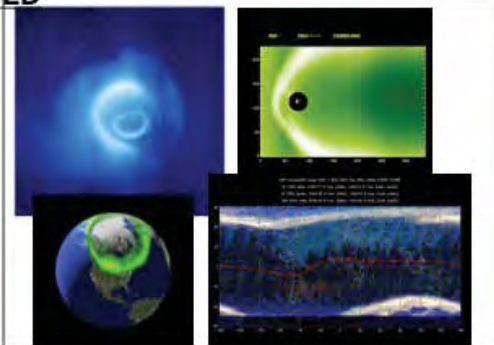
- None



Geospace Observer from Large Distance



GOLD



Mission Implementation Description:

- *Single spacecraft to image the magnetosphere, the plasmasphere, and the ionosphere
- *Location: Lunar orbit (Other possibilities include L1, heliocentric Earth synchronous)
- *Attitude Control: 3-axis stabilized
- *Instruments (all Imaging)
 - Magnetospheric Imaging Coronagraph (MAGIC)
 - Magnetotail Reconnection Imaging Exp (MATRIX)
 - Plasmaspheric Imaging Experiment (PIXI)
 - Ionospheric Imager (II)
- *Payload resources required (100 kg/80 W/250 kbps)

Measurement Strategy: Images obtained 1/min at a resolution of 1000 km to reveal global magnetospheric structure

Science Objectives:

1. Understand the dynamic coupling of the magnetospheric system to solar wind variations
2. Understand the evolution of the ionosphere in response to the magnetospheric driver
3. Understand critical global parameters and dynamics that drive physical prediction models

Associated RFAs:

F1, H2, J1

Enabling Technology Development:

- No enabling technology necessary

Enhancing Technology Development:

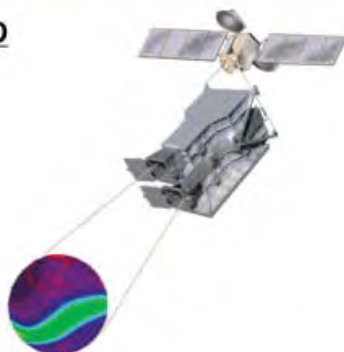
- Lightweight advanced baffle design
- High-performance computing on board, or large continuous data downlink
- Lightweight optics



Global-scale Observations of the Limb and Disk



GOLD



Science Objectives:

1. Understand how geomagnetic storms alter the thermosphere and the low-latitude, nighttime ionosphere
2. Quantify the global-scale response of the thermosphere to solar extreme-ultraviolet variability
3. Determine whether atmospheric waves and tides have a significant effect on thermospheric temperature structure
4. Quantify how vertical ion drifts, as manifested in the structure of the equatorial anomaly, affect the occurrence of ionospheric irregularities

Associated RFAs:

F3, H2, H3, J4

Mission Implementation Description:

- *Number of spacecraft: 1
- *Location: Geostationary
- *Flight on commercial communications satellites
- *Number of instruments: 1
- *Type of instrument: remote, TRL-level: 6 or greater
- *Payload resources required (30 kg/30 W/5.0 Mbps)

Measurement Strategy:

- *Simultaneous disk images of daytime T_n and O/N_2 ratio
- *Disk images of peak electron densities and low latitude irregularities at night
- *Limb measurements of O_2 density profiles and T_{exo}

Enabling and Enhancing Technology Development:

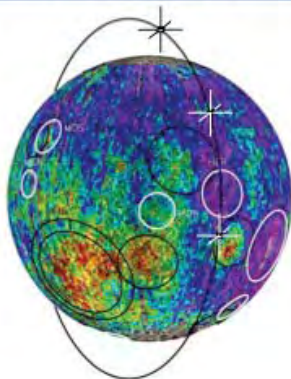
- Enabling Technology - Inexpensive access to geostationary orbits
- Enhancing technology – Solar irradiance and solar wind measurements



Heliophysical Plasma Physics In Lunar Orbit



HILO



Science Objectives:

To understand the:

- Fundamental physics of plasma interactions with magnetic fields from kinetic (particle) to fluid behavior, using *lunar magnetic anomalies* of a few km to ~100s of km size – from less to greater than thermal proton gyro-diameter..
- Ion & electron decoupling from the magnetic field.
- Formation of (mini-) magnetospheres & shocks (for super-Alfvénic flow)
- Dynamics of the Earth's distant (>~60 Re) magnetotail & reconnection, using *lunar shadowing* of electrons to determine the topology of magnetic fields & their velocity.

Mission Implementation:

- Multiple spin-stabilized spacecraft in lunar polar orbit with ~10 km periselene altitude and variable separations
- Measurements: fast 3D ion & electron plasma, magnetic & electric fields, plasma & radio waves, suprathermal particles, EM sounder for electron density tomography
- Instruments: *in situ* in addition to remote sounder & radio waves, all TRL-6 or higher
- Payload resources required : ~30kg, ~30 W, ~4kbp/s
- Measurement strategy: High time resolution burst mode in regions of interest; store & dump data to ground

Associated RFAs:

- F1. Understand magnetic reconnection
- F2. Understand plasma processes that accelerate & transport particles.
- F3. Understand plasma and neutral interactions
- H4. Apply space plasma physics to magnetic shielding
- J1. Characterize the space environments

Enabling and Enhancing Technology Development:

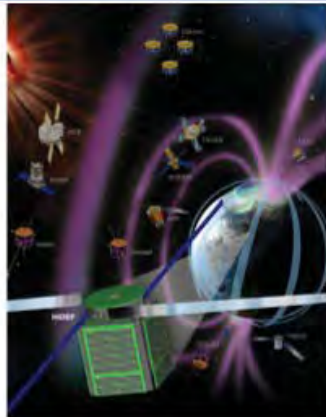
- EM sounder technology for distance determination.
- Study of flight dynamics for low altitude lunar orbit.
- Study of electron density tomography



High-latitude Dynamic E-Field Explorer



HiDEF



Science Objectives:

HiDEF will observe and resolve the inadequately understood high-altitude magnetosphere-ionosphere-thermosphere global electric field forcing, coupling dynamics, and evolution over a wide range of spatial and temporal scales, providing the last major link in the Earth-Sun connection.

Associated RFAs:

F3, H2

Mission Implementation Description:

- 90 satellite constellation (20% redundancy)
- Low Earth Orbit (515-675 km)
- Attitude control: spin stabilized
- Electric field sensor – measures in-situ DC and AC components
- TRL 8/9
- Mass- 1.08 kg/spacecraft, Power – 0.82 W avg/spacecraft, Telemetry- 619 Mb/constellation

Measurement Strategy:

Global ionospheric electric field measurements

Enabling and Enhancing Technology Development:

- Picosatellite constellation (global science platform)
- Miniaturized science payload, communications hardware, and attitude sensors
- Advanced tracking and ground station coordination



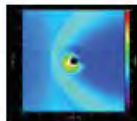
Imaging Geospace Electrons Using Thomson Scattering



We can observe disruptive solar events such as CMEs from the Sun through the heliosphere.

Thomson scattering observations of geospace electrons will complete our chain of Sun-to-Earth observations, enabling global specification and forecasts of the ionosphere-plasmasphere-magnetosphere system in response to solar drivers.

Simulated Thomson scattering images of geospace electrons (right, no noise), show the bow shock, magnetosheath, magnetopause, and the plasmasphere in a SAMI3-LFM model scene.



Science Objectives:

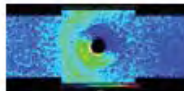
- Determine how electrons in the magnetosphere, plasmasphere, and ionosphere are redistributed in response to solar wind forcing
- Understand mechanisms of solar wind plasma entry into the magnetosphere by globally imaging structures along the magnetopause and magnetospheric boundary layers

Associated RFAs

H2, J4

Mission Implementation Description:

- One 3-axis stabilized spacecraft
- 30- R_E circular, inertial polar orbit
- Four imagers (two "geo-coronagraphs", two white-light, magnetospheric imagers). Simulated image with noise shown above, right
- Payload mass estimate (instruments and spacecraft): ~1700 kg



Measurement Strategy:

Observe Thomson scattered light to **directly image geospace electron densities** and their interactions with the solar wind

Enabling and Enhancing Technology Development:

NASA-sponsored coronagraphs and STEREO SECCHI/Heliospheric Imagers have successfully imaged structures in the solar wind (CMEs and CIRs) by observing Thomson scattered light. Leveraging NRL expertise, we will adapt these techniques to **directly image geospace electrons for the first time**.



Other enabling technologies required for this mission:

- Large format focal plane detector arrays and light-weight optics
- Formation flying satellites (potentially)
- Next generation space environment forecasting models that couple all regions of geospace including the bow shock, magnetosheath, and magnetopause



In-situ Diagnostics of Universal Plasma Processes



Science Objective:

To use the Earth's local plasma laboratory to diagnose universal plasma processes

Processes to study:

Alfvén waves, double layers, electron and ion phase space holes, two stream instabilities, AKR-radiation, pitch angle scattering, surface waves, filamentation, flow shears, Langmuir waves, etc.

Problems to solve:

- resolve spatial and temporal ambiguities in plasma processes
- understand plasma dynamics and evolution
- understand how processes of different scale sizes interact with each other

Mission Implementation Description:

Number of spacecraft: 2
 Attitude control: Spin stabilized
 Orbit: 350 x 5000 km, Incl. 80°
 Orbit phase 1: String of pearls
 Orbit phase 2: Magnetic conjunctions
 Each satellite has full complement of fields- and particle- sensors and imagers (in-situ and remote)
 Payload resources required (per spacecraft):
 Mass 75 kg Power 45 W Telemetry 2.0 Mbps
 Science team with Astrophysical and Plasma physics expertise

Associated Research Focus Areas:

F2, F3

Measurement Strategy:

High temporal resolution plasma measurements with high spatial and temporal imaging

Large satellite memory allowing interesting data periods to be selected for downloading

Integrated sensors for optimal operation and science return

Enabling and Enhancing Technology Development:

Robust, in-expensive, light weight, de-spun imager



Interstellar Explorer - An Interstellar Precursor Mission



Science Objectives:

- 1) Explore the influence of the interstellar medium on the Solar System, its dynamics, and its evolution*
- 2) Explore the impact of the solar system on the interstellar medium as an example of the interaction of a stellar system with its environment*
- 3) Explore the outer Solar System in search of clues to its origin, and to the nature of other planetary systems*

*From NASA's Interstellar Probe STD Report

Associated RFAs: F2, F3, H4, J1, J3

Mission Implementation Description:

- Number of spacecraft: 1
- Location: Deep space; solar system escape
- Attitude control: Spin stabilized
- Number of instruments: 10
- Type of instrument(s): 7 in situ, 3 remote, TRL 5-8
- Payload resources required: 47 kg, 40 W, 7.8 kbps (~35% margins)

Measurement Strategy:

Slow sky scans with spin stabilization; store and dump to Earth periodically (two 8-hr downlinks per week) over 30 years

Enabling and Enhancing Technology Development:

Enabling:

High efficiency, low-specific-mass Stirling radioisotope generators

Radioisotope electric propulsion (REP)

Low-mass, low-power instruments

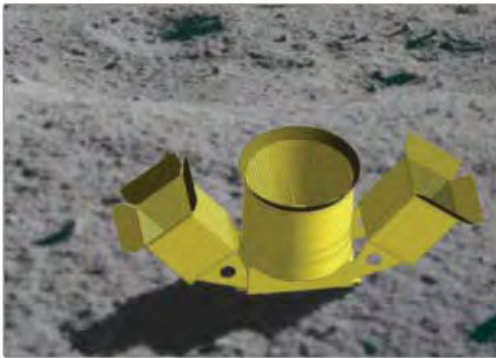
Enhancing:

Ares V launch vehicle with Centaur upper stage or NERVA-derivative nuclear upper stage

TRL-9 400m+ dia solar sail with areal density not to exceed 1 g m⁻²



Lunar Dust Observatory



LDO Science Objectives:

To investigate the interplanetary and interstellar as well as the local lunar dust environment as function of the solar wind conditions.

By means of a Dust Telescope the Dust Observatory will (1) provide the distinction between interstellar dust and interplanetary dust of cometary and asteroidal origin, (2) determine the elemental composition of impacting high-speed dust particles, and (3) monitor the fluxes of various dust components as a function of direction and particle masses. In addition it provides the characterization of the local lunar dust environment.

Associated RFAs:

F3-4, H4-4, J1-1

Mission Implementation Description:

- Number of spacecraft: Lunar Lander
- Location: Lunar surface
- Attitude control: Articulation of the Dust Telescope
- Number of instruments: suite of > 3 dust analyzers
- Type of instruments: in-situ dust analyzers, TRL-level: 4 - 5
- Payload resources required (30 kg, 50 W, 100 kbps)

Measurement Strategy:

- Continuous measurement
- Staring observations in various directions

Enabling and Enhancing Technology Development:

- Develop flight instrumentation for dust trajectory measurement and for in-situ chemical analysis of fast moving interstellar and interplanetary dust
- Develop flight instrumentation for the measurement of slow moving electrically charged dust.



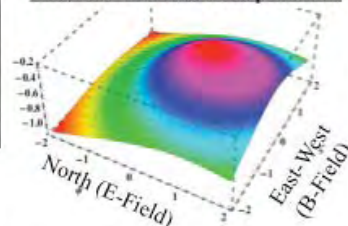
Lunar Surface Solar Origins Explorer



Lunar Limb "Knife-Edge" for solar coronal occultation

Solar Wind Ion Implantation Injects Solar Coronal Composition Into the Lunar Surface and Solar Energetic Ions (SEP) Sputter Surface Atoms

Lunar He^+ Antisolar Pickup Ion Flux



LunaSSOX Science Objectives:

- Upstream solar wind plasma ion contributions to lunar surface volatile composition via orbital measurements
- Global distribution of volatile and refractory surface composition via pickup ions from SEP ion sputtering
- Solar F-corona plasma composition & near-solar dust interaction via remote spectroscopic & doppler imaging

Associated Heliophysics RFAs: F3, J4

Mission Implementation Description:

- Number of Spacecraft : 1 or more
- Location: lunar 50-km polar orbit, day-night orientation
- Attitude control: 3-axis stabilized (ram, nadir, solar)
- Instruments:
 - in situ low-energy ion-neutral and energetic heavy ion mass spectrometers, magnetometer (20 kg/20 W)
 - remote UV-VIS-IR spectroscopic imagers (30 kg/30 W)

Measurement Strategy:

- Lunar orbit for near-lunar plasma ion, gas, mag, SEP
- Lunar limb occultation from orbit for solar corona obs.

Enabling and Enhancing Technology Development:

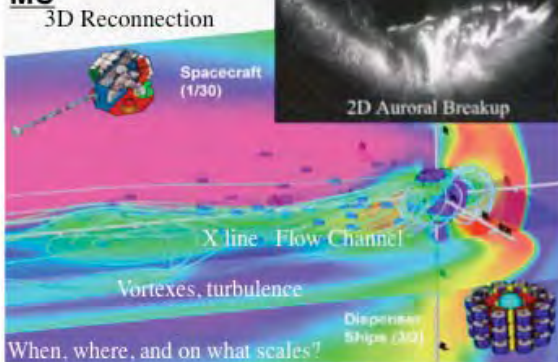
- High resolution plasma and neutral gas composition spectrometers integrated to energetic ion detectors for complete characterization of plasma/SEP interactions
- Compact steerable high-resolution UV-VIS-IR spectroscopic imaging system for solar F-Corona, lunar surface & atmosphere, and other geospace observations – not diffraction limited by s/c occulter !
- Lightweight solar-powered spacecraft bus system for flexible lunar orbital and solar observation operations



Magnetospheric Constellation Mission



MC



Mission Description

- Constellation of 30-36 ST-5 class s/c
- 15° inclination, nested orbits
- Apogees from 7-27 RE, $\Delta V = 814$ m/s
- Per s/c: 20 kg, 15 W, 1 kbps, 1° pointing

Measurement Strategy

- Synoptic vector measurements of magnetic field, plasma flow & energetic particles
- Mean spacecraft separation: 2 RE
- Time resolution: 10 sec
- Mission targets are plasma sheet and low latitude magnetopause

Science Objectives

- Determine how the magnetosphere stores, processes, and releases energy from the solar wind interaction:
- How does the magnetotail behave?
- How are particles injected to form the radiation belts?
- How does the magnetopause respond to the solar wind?

Enabling Technology Development

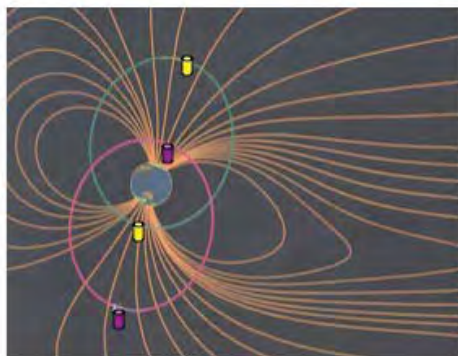
None

Technology Requirements

- ST-5 design-experience base
- Fabrication, assembly and testing techniques from Iridium, GPS, other commercial, DoD constellations



Magnetospheric Sentinels



Mission Implementation Description:

- Number of spacecraft – Ideally, 4; 2 in each orbit
- Location – Molniya orbits (+ & - 63°); 6, 8 or 12 hr period
- Attitude control – in practice, either spinner or 3-axis stabilized; ideally, stabilized
- Number & Type of instrument(s) – tri-spectral FUV imager + telescope for hi-res; possible proton &/or X-ray imagers (Sentinel A & B) + in-situ particle and fields
- Payload resources required – 80 kg/60 W/200 kbps

Measurement Strategy:

- Continuous observations of global-scale auroral emission in both hemispheres

Science Objectives:

- Interhemispheric differences in acceleration/deposition
- Magnetospheric modes (SMC vs. load/unload)
- In situ Poynting flux measurements vs. auroral energy
- X ray imaging of dispersionless injections/Proton aurora
- (Monitoring/context – not science, but important)

Associated RFAs: F3, H2, H3

Enabling and Enhancing Technology Development:

- Space Qualification of high resolution (1024 X 1024) electron amplifying CCD detectors
- Implementation of controlled lossy compression for science missions



Maneuverable Near-Space Platform



Science Objectives:

- High res. solar imaging: photosphere, chromosphere, corona (incl. streamers, solar wind, CMEs); auroral imaging; limb sounding, absolute TSI...
- High res. spectral, spatial, temporal, Earth imaging, pollution (NO_2 , SO_2 , O_3), ocean color, hurricane tracking, wind speed.
- Large aperture astrophysics optical/IR telescope/interferometer

Associated RFAs: TBD

Mission Implementation Description:

- One spacecraft (Airship)
- Location: Near space (> 18 km altitude)
- 3-axis stabilized craft with engines, with LMATC disturbance-free payload (DFP)
- Multiple instrument capacity (1-10)
- In-situ & remote sensing, facing out or down
- Payload resources TBD

Measurement Strategy: Large-aperture, long-duration, stable-pointing, near-space platform

Enabling and Enhancing Technology Development:

- Long duration (months), high altitude Airship [under design by DoD]
- Image stabilization (DFP; TRL 6)
- Test platform for new technologies
- Calibration underflight



Neutral Ion Coupling Explorer



NICE Science Objectives: Understand coupling between planetary ionospheres and their upper atmospheres mediated by strong ion-neutral coupling [Science Plan, 2006]

- (1) How do the large scale atmospheric dynamics control the Earth's ionosphere.
- (2) What causes the day to day variability in the Earth's ionosphere.
- (3) What causes the ionospheric plasma enhancement during storms.

Associated RFAs: F3, F4, H2, J4

Mission Implementation Description:

- Number of spacecraft: 1
- Location: circular orbit alt. = 550 km, incl. = 24°
- Attitude control: Nadir pointed 3-axis stabilized
- Instruments: (1) Fabry-Perot (remote), (2) FUV imager (remote), (3) EUV profiler (remote), (4) Ion Velocity Meter (in situ/remote), all TRL = > 6.
- Payload resources required (mass/pwr/tlm): 72.4kg/59.4W/30.6 kb/s (S band) Measurement Strategy: Low inclination orbit remote instruments look at northward limb, FUV/EUV characterizes thermosphere/ionosphere. Wind vector profiles are measured on same limb. Equipotential field lines allow interpretation of in situ ion drift as E field in same limb region. Obtains composition (neutral and ion), neutral winds and temperatures.

Enabling and Enhancing Technology Development:

All required technologies are currently available to perform the NICE baseline mission, however technology development will increase the value of the retrieved data.

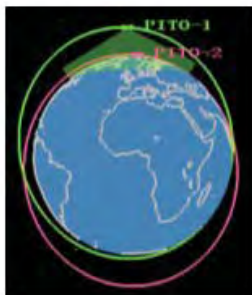
1. Development of observation-specific on-board data compression schemes.
2. Development of inversion and tomographic algorithms for 3-di interpretation.
3. Higher dynamic range (speed) photon counting FUV detectors would simplify calibrations and thus improve data quality.



Paired Ionosphere-Thermosphere Orbiters



PITO



Science Objectives:

- Combine in situ data, imaging and profiling to unravel the complex interplay between process on different scales and in different regions and assess how the I-T system responds to magnetospheric and neutral forcing, including
- The causes of ionospheric density irregularities < 1000 km
- Composition changes in the aurora
- High-latitude electrodynamical control of the global circulation of the atmosphere
- Connections between equatorial depletions and atmospheric disturbances

Associated RFAs: F2, F3, H2, H3, J1, J4

Mission Implementation Description:

- Number of spacecraft: 2
- Location: LEO (200 x 2000 km)
- Attitude control: 3-axis stabilized
- Number of instruments packages: 4
- Payload resources required: 400 kg

Measurement Strategy:

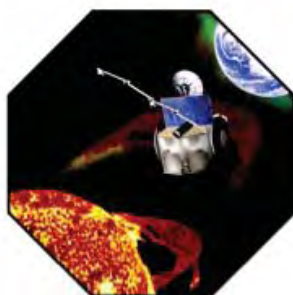
Paired satellites for simultaneous observation of large and small scale ionosphere-thermosphere phenomena in two regions of the atmosphere and the coupling between them

Enabling and Enhancing Technology Development:

- None
- Enhancing technology: Spaceborne lidar would enhance the mission



PERSEUS Mission “Investigating heliospheric dynamics from L₁”



PERSEUS

Science Objectives:

Explore changes in heliospheric material and flow impacting Earth and planets, outward to the heliospheric outer boundary
Understand the relationship between CMEs and CIRs
Investigate transient phenomena effects on Earth and planetary bodies
Understand plasma transport and solar wind physics
Measure the societal impacts of solar events

Associated Research Focus Areas:

Understand the structure and dynamics of the Sun and solar wind
Determine heliosphere evolution and its interaction with the galaxy
Understand the response of planet magnetospheres and atmospheres
Discover how heliospheric magnetic fields evolve
Understand coupling across multiple scale lengths
Develop prediction of solar activity and solar disturbance evolution
Specify and enable prediction of changes to the Earth's environment

Mission Implementation Description:

Number of spacecraft: One, Pegasus launched
Location: L₁
Attitude control: 3-axis stabilized, sun pointing
Number of instruments: 4
Type of instruments: 2 remote sensors (All-Sky Imager, Coronagraph), 2 *in situ* monitors (Plasma Monitor, Magnetometer) (TRL 6-9)
Payload resources required mass = 17.5 kg, pwr = 24 w,
tlm = 10⁴ K bits s⁻¹ to USN

Measurement Strategy:

All-the-sky all-the-time remote-sensing imagery from L₁
from 2.5 solar radii to ~180° anti-solar
L₁ ground truth and *in-situ* monitor forecast capability

Enabling and Enhancing Technology Development:

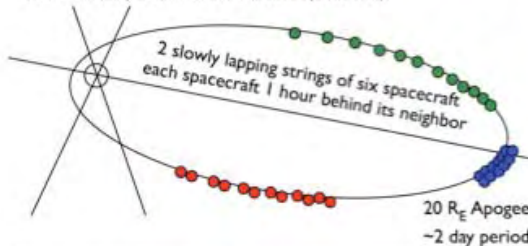
Light-weight 3-axis stabilized s/c bus technology enables a Pegasus launch to L₁ for long-duration heliospheric science exploration
Light-weight hemispheric imager concept gives “all sky, all time” coverage; excludes solar background illumination.
SMEI and NASA STEREO Heliospheric Imager remote sensors prove and enable concept
3D MHD heliospheric models provide 3D interpretation
3D reconstructions of the heliosphere at high resolution on super-computers allows modeling in near real time
Further ground truth verification provided by *in situ* and remote-sensing measurements from multiple missions



The Profile mission



• Profile achieves multiple science objectives by using different formations throughout the mission.
 • “lapping” string-of-pearls formation (two identical strings of six spacecraft each per mothership) allows evolution of Profile over time (e.g. red, blue, and green formations below will naturally result from orbital dynamics)



Science Objectives:

- Understanding of the effects of disturbances from the Sun, the dynamics of substorms from the tail, and the nature of boundary layer motions on the flanks
- How do these disturbances propagate? What roles are played by large-scale, medium-scale, and small-scale structures?
- What is the global structure (convection, magnetic field, plasma density and temperature) of the plasma sheet and how does it change during substorms?

Associated RFAs:

F1, F2, H2, J1, J4

Mission Implementation Description:

- 12 daughter spacecraft per mothership (for 24 spacecraft, use two motherships with opposing apogees)
- 7000 km x 20-25 Re, 10-15 degrees inclination
- Spin stabilized, no propulsion
- Vector magnetometer, 3-D plasma analyzer (<30 keV)
- in situ measurements using high-TRL instruments
- bus+payload requires 17 kg, 30 W, 2 kbps orbit-averaged

Measurement Strategy:

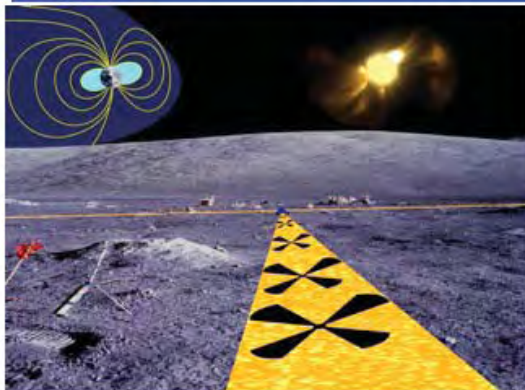
- Simultaneous data from all x-y cross-sections during a year as apogees precess.
- Tight “superclusters” near apogee
- Separation of spatial from temporal variations
- Repeated passes in quick succession through important regions
- Simple identical instruments provide the most science return per dollar

Enabling and Enhancing Technology Development:

- Mass-production of 12 (or 24) identical daughter spacecraft, based on ST-5 bus
- Centrifugal slingshot deployment system that can accommodate 12 daughter spacecraft per mothership
- Similar miniaturization as required for MAGCON
- For extended Profile mission (beyond 2 years), up to 6 hour eclipses could be mitigated by improved battery technology – not needed for prime 2 year mission
- Another possibility would be the use of non-volatile memory and no batteries, letting the spacecraft go to sleep during eclipse periods



Radio Observatory for Lunar Sortie Science



ROLSS Science Objectives:

- Understand particle acceleration in the outer solar corona by imaging solar radio bursts in that region of space (for the first time)
- Determine shock acceleration geometry in outer corona
- Determine acceleration source(s) and location(s) for complex solar radio bursts
- Understand fine structure in solar radio bursts and its relation to magnetic field and solar wind structures

Associated RFAs:

F1, F2, H1

Mission Implementation Description:

- Radio interferometric array deployed on lunar surface
- 3 arms ~1.5m wide x 500 m long of thin polyimide film with dipole antennas and leads deposited on film
- ~16 antennas per arm connected to central hub
- Hub has radio receivers, solid state memory, solar arrays, phased array downlink, thermal control, etc.
- Deployed with astronaut support (lunar sortie); rover attachment permits unrolling of film on surface
- Latitude w/ 30 deg of lunar equator = coronal viewing
- Estimated resources: 300 kg, 130 W (day), 70 Mbps

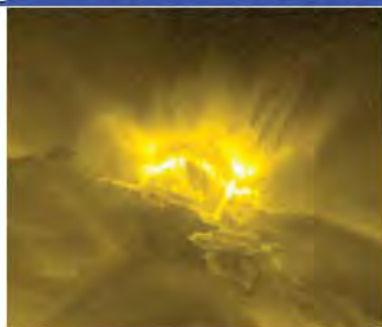
Measurement Strategy: aperture synthesis imaging

Enabling & Enhancing Technology Development:

- Enhance and validate polyimide film/antenna system design and TRL
- Develop complete ultra low temperature/ultra low power suite of electronics
- Develop ultra low temperature/ultra low power solid state recorder
- Apply state of art battery technology to reduce mass and to improve battery survival temperature range
- Confirm rover characteristics for deployment



Reconnection and Microscale Mission



TRACE 195A post flare loops and current sheet. Notice the dark voids threading the FeXXIV emission that reveals the current sheet. Higher resolution is required to image the substructure in reconnecting plasma.

Mission Implementation Description:

- One Geostationary 3-axis stabilized spacecraft
- Payload: 1600kg/1200W/1.3TB/day (30% reserves included)

Coronal Imaging Spectroscopy Instrumentation:

- High resolution EUV/UV spectrograph (0.25"/pixel)
- X-ray imaging Spectroscopy (2" imaging, 2eV resolution from 0.2 to 10keV, photon counting)
- Hard X-ray Imaging Spectroscopy (~15"/pixel, 5-80keV)
- Multi wavelength high resolution EUV/UV imagers (0.1"/pixel)

Measurement Strategy:

- Observe the site of particle acceleration.
- Quantify the inflows and outflows associated with reconnection.
- Plasma properties from 1-50Mk with high spatial & temporal resolution.
- Detect the sub-structures responsible for energy conversion.

RAM Fundamental Question: *What are the underlying physical processes by which high energy particles and radiation are created throughout the plasma universe?*

Science Objectives:

- What micro-scale instabilities lead to global effects?
- Where are the regions of particle acceleration?
- What are the mechanisms that lead to reconnection?
- Where are the reconnection regions and what is their topology?

Associated RFAs:

F1, F2, H1

Why is RAM important?

RAM will locate and measure the high energy radiation and particles at their source in the Sun's outer atmosphere.

When will RAM be ready?

RAM is ready for a Science Definition Team.

Enabling and Enhancing Technology Development:

Enabling Technologies (current TRL estimate):

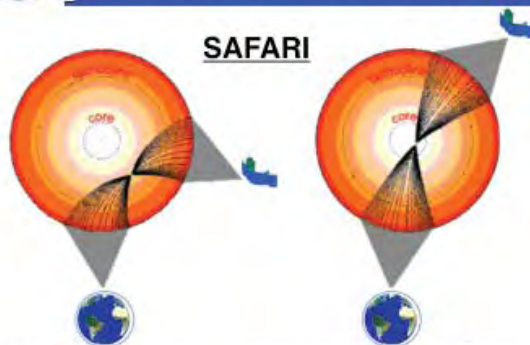
- Large format, high count rate X-ray calorimeter TRL 4-5: Based on Astro-E II and IXO development efforts.

Technologies at TRL ≥ 6

- Hard X-ray focusing optics TRL 6: based on HERO, HEFT
- Extendable Optical Bench TRL 7: RAM can re-use e.g. the NewSTAR deployable mast.
- Image stabilization techniques TRL 6: RAM extends techniques from TRACE and SOHO/MDI and SDO/AIA missions.
- Multilayers for the high resolution imager optics TRL 9: uses same as TRACE and SDO/AIA heritage.



Solar Activity Farside Investigation



Measurement Strategy:

- Safari will acquire simultaneous measurements of photospheric velocity and magnetic fields from two separate and varying solar longitudes (one near-Earth) to probe the deep interior of the sun and track the evolution of magnetic activity

Mission Implementation Description:

- Single spacecraft launched by Taurus class L/V
 - Operational orbit: Earth-leading, [x] 2 yr duration
 - Spacecraft pointing: [x] 0.5 [x] control, knowledge [x] 0.1 [x]
 - Weekly data volume: ~30 Gbit
- Compact Doppler-magnetograph
 - Instrument pointing: [x] 0.5 arc-s (w/ fast steering mirror)
 - 8 kg, 15 W, Average data acquisition Rate [x] 42 kbps
 - up to 5" spatial resolution
 - Velocity sensitivity < 10 m/s/pixel
 - Longitudinal magnetic field sensitivity [x] 3G

Science Objectives:

Safari will quantify:

Where in the sun solar variability originates
How magnetic fields emerge and evolve on the solar surface

How solar magnetic fields map into the global heliospheric structure

These objectives will be achieved by using time-distance and other helioseismology techniques to probe the deep solar interior and by measuring magnetic fields over a wide range of solar longitudes.

Associated RFAs:

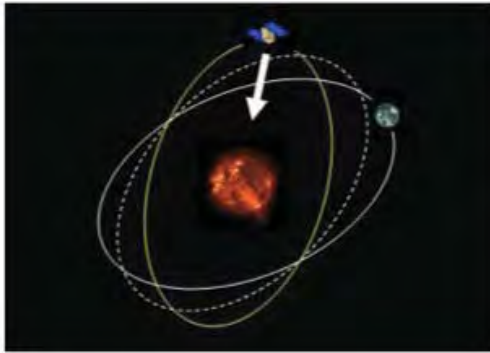
F4, H1, J2

Technology Development:

- Compact Doppler magnetograph
 - magneto-optical filter TRL 4



JAXA SOLAR-C Plan-A



Science Objectives:

- Understand the internal structure of the Sun and the solar dynamo mechanism
- Understand the mechanism for high-speed solar wind
- Understand the variability of environments (space weather) in inner heliosphere with distance from the plane of the ecliptic

Associated RFAs:

F1, F2, F4, H1, H3, H4, J1, J2, J3, J4

Mission Description:

- A three-axis stabilized spacecraft in a high-inclination orbit by assists of JAXA ion engines and earth flyby
- Maintains 1AU distance
- Photospheric magnetic and Doppler velocity field observation with transition-region & coronal imaging and spectroscopic observations

Measurement Strategy:

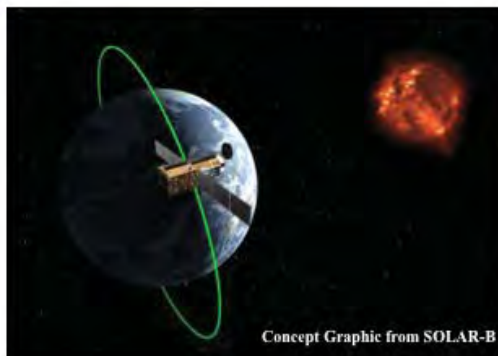
- Helioseismology from high-inclination orbit in coordination with an observatory near and/or on the Earth
- Direct access to polar regions as a source of high-speed solar wind and as critical area for solar dynamo
- Auxiliary in-situ measurements of inner heliosphere at ~1AU with various orbit inclinations

Enabling and Enhancing Technology Development:

- High-thrust and long-life ion engines
- High-level power system for ion engines
- High-data rate interplanetary telemetry



JAXA SOLAR-C Plan-B



Science Objectives:

- Understand the solar chromospheric and coronal heating mechanisms by enhanced spectroscopic diagnostic capability
- Understand the plasma dynamics throughout the outer solar atmosphere by high-throughput instruments
- Understand the acceleration mechanism for fast and slow solar winds

Associated RFAs:

F1, F2, F4, H1, H3, H4, J1, J2, J3, J4

Mission Description:

- A three-axis stabilized spacecraft in a sun-synchronous polar orbit or geosynchronous orbit or equivalent
- High-throughput visible and UV imaging and spectroscopy, a coronal imaging, and EUV imaging spectroscopy

Measurement Strategy:

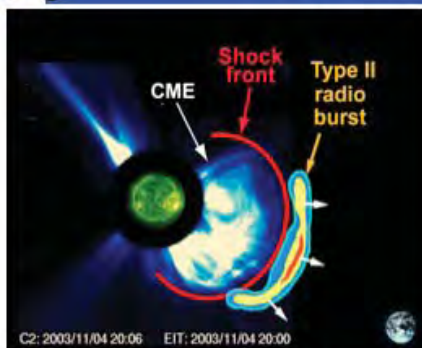
- Emphasis on high-spatial and high-time resolution spectroscopy for investigating dynamic chromosphere and transition region with observations of photosphere and corona
- Higher spatial resolution in transition region and coronal observations than that for Hinode

Enabling and Enhancing Technology Development:

- Stringent contamination control for UV and EUV instruments
- Image stabilization technique for all instruments
- High-data rate telemetry (10-100 times higher than that used in Hinode)



Solar Imaging Radio Array



SIRA will image radio emission from CME-driven shocks and flare electron beams propagating into the inner heliosphere at frequencies inaccessible to ground based radio telescopes.

SIRA Science Objectives:

- Enhance understanding of interplanetary propagation and evolution of coronal mass ejections (CMEs) using radio images of CME-driven shocks, plasmoids, and electron beams
- Enhance understanding of particle acceleration & transport using images of radio bursts produced by electrons
- Use radio imaging near Sun to predict hazardous space weather
- Obtain and analyze the first full-sky maps from 0.1 to 15 MHz

Associated RFAs:

F1, F2, H1

Mission Implementation Description:

- Microsat constellation of 12-16 identical s/c
- Microsat: 30 kg (wet), 90 W, use of ST-5 bus
- Payload: 10 kg/sat, 10 W/sat
- Carrier/mother: buffers/xmits (Ka-band) d/l
- ΔV : 100 m/s (carrier), ~7 m/s (microsat)
- Ellipsoid constellation, 1 km diameter at L1
- 2 high-heritage antennas & receivers per s/c
- Image synthesis done on the ground at SIRA Science Centers

Measurement Strategy:

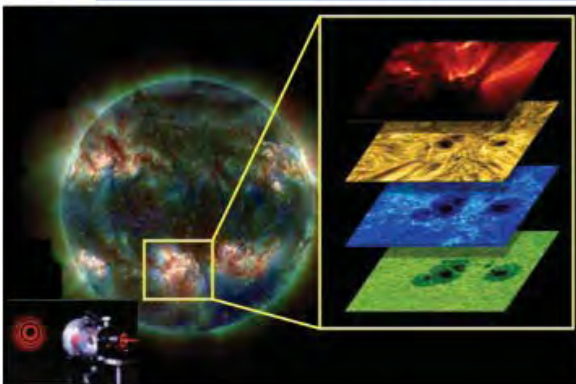
- Imaging at ~12 frequencies corresponding to $\sim 2 R_{\text{SUN}} - 1 \text{ AU}$
- 2-bit Nyquist sampling at each frequency
- ~2.4 GB science data per day per microsat
- "Snapshot" processing on ground for space weather prediction

Enabling and Enhancing Technology Development:

- Low cost intersatellite ranging with 3 m accuracy to ranges of 50 km is simple to build, but has not been tested in flight
- SIRA and other Ka-band users need more ground station capacity



Solar MAgnetized Regions Tomograph



SMART Science Objectives:

1. Reveal how magnetic fields extend into the solar corona, where measurements do not exist.
2. Understand when, why, and how is magnetic energy released in solar flares
3. Determine what heats the solar corona

Associated Heliophysics RFAs:

F1, H1, J1, J2

Mission Implementation Description:

- One spacecraft at polar, Sun-synchronous (600 km) orbit, with solar-pointed attitude control
- One remote sensing vector magnetograph (TRL 5)
- Relatively light-weight (600 kg), low-power (600W), with a telemetry of approx. 4 Mbps

Measurement Strategy:

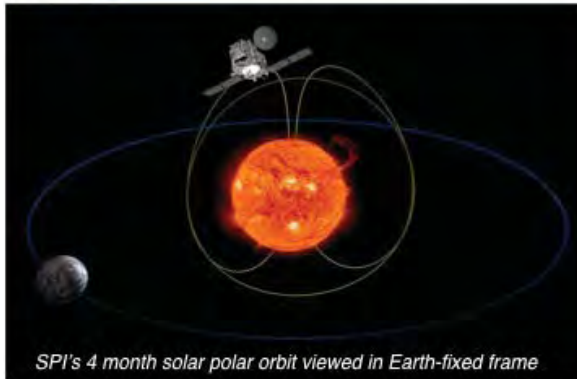
Provide the first-ever three-dimensional tomographic magnetic field measurements of solar active regions and the quiet Sun in sufficiently high quality to yield an unprecedented science return

Enabling and Enhancing Technology Development:

- Lithium-niobate, solid, Fabry-Perot etalon filter
- A 50-cm aperture solar optical telescope
- Vector magnetograph able to switch to a number of magnetically sensitive spectral lines formed at different heights in the solar atmosphere
- Small integration time, (a few minutes) to enable nearly simultaneous coverage of the various layers
- High cadence, to enable detailed evolution coverage
- **Previous experience / heritage exists through the balloon-borne Flare Genesis Experiment**



Solar Polar Imager (aka POLARIS)



Mission Implementation Description:

- SC in highly inclined ($\sim 75^\circ$) 3:1 Earth-resonant heliocentric 0.48 AU orbit
- Low-thrust trajectory with solar sail delivery (electric propulsion is another option)
- 5 remote sensing, 3 in-situ instruments, 3-axis stabilized s/c 43 kg, 52 W, Avg. Acquisition Rate ~ 100 kbps

Measurement Strategy:

- Surface & interior flows for helioseismology
- Polar magnetic fields and flux transport
- Polar coronal imaging in white light and EUV
- UV Spectrometer for outflow velocities
- *In situ* magnetic fields, solar wind and energetic particles
- Total solar irradiance variability

SPI Science Objectives:

- Dynamo: Helioseismology & magnetic fields of polar regions
- Polar view of corona, CMEs, solar irradiance for structure, evolution and space weather prediction
- Link high latitude solar wind & energetic particles to coronal sources

Associated RFAs:

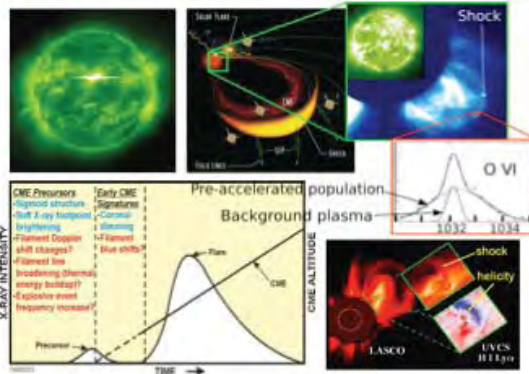
F2, F4, H1, J2, J3

Enabling Technology Development:

- Solar sail (current launch vehicles)
- Constellation may enable SEP implementation



Space Weather Imaging Sentinel



SWIS Science Objectives:

- Determine the most relevant observational signatures of flare, CME, and Solar Particle Event (SPE) eruption
- Identify precursor signatures which can be used to forecast flare, CME, and SPE eruption
- Identify what is needed to improve our ability to nowcast and forecast space weather & SPEs
- Identify the physical mechanisms of mass flow and energy release in the solar atmosphere
- Determine the interaction and connectivity of structures throughout the solar atmosphere

Associated RFAs: F1, F2, J2

Mission Description:

- 1 spacecraft, 5 Hi-TRL instruments
- L1 or Geo or 98° , 600 km sun-synch orbit
- continuous solar viewing
- 3-axis stabilized, 30 arc-sec pointing capability
- Payload: 40 kg, 53 W, 2.2 Mbps

Measurement Strategy:

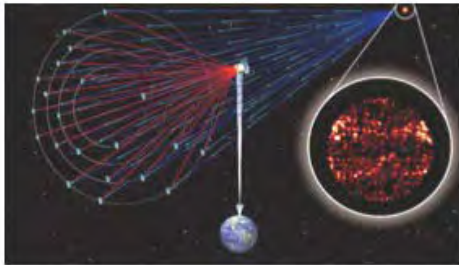
- UV/EUV Imaging Spectrograph for flow velocities & energy buildup & release signatures, both on the disk and off-limb (out to 3 Rs)
- Filter Magnetograph for surface magnetic field measurements
- Chromospheric/Coronal EUV Imagers for morphology and dynamics
- Energetic Particles (SEP) measurements for event characterization
- Coronagraph for detection & characterization of Halo CMEs

Enabling and Enhancing Technology Development:

- High cadence imaging spectrograph development
- Low mass/power instrumentation
- Advanced communication/DSN for future deployment to Sentinel or remote locations



Stellar Imager



SI is a UV/optical deep-space telescope to image stars like the Sun with 0.1 milli-arcsec resolution, to help understand the solar dynamo, the internal structure and dynamics of magnetically active stars, how magnetic activity drives space weather on time scales of years to billions of years, and how that affects planetary climates and habitability.

Mission Implementation:

- *Interferometer with 9 to 31 formation-flying spacecraft. The number of mirror elements determines the time needed to complete an image, and thus the number of possible targets
- *Location: Sun-Earth L2
- *Attitude control: 3-axis stabilized
- *Type of instrument(s): remote sensing imagers
- *Payload resources: up to 5000kg/3000W/1-5Mbps

Measurement Strategy:

- UV/optical interferometric spectral imaging
- angular resolution of images better than 0.1 milli-arcsec
- spectral resolution $R=100$ requirement, $R=20000$ goal
- measure internal structure & rotation of select stars with $<50,000$ km resolution in & below convective zones

SI Science Objectives:

Develop and test a predictive dynamo model for the Sun by:

- *observing the patterns in surface magnetic activity for a large sample of Sun-like stars* (with ~1000 res. elements on surfaces of nearby stars)
- *imaging the structure and differential rotation of stellar interiors* via asteroseismology with over 30 resolution elements on stellar disks
- *carrying out a population study of Sun-like stars* to determine the dependence of dynamo action on mass, internal structure, flow patterns, and time. This will enable testing of dynamo models over a few years of observations of many stars, instead of over many decades using only the Sun.

Associated Research Focus Areas:

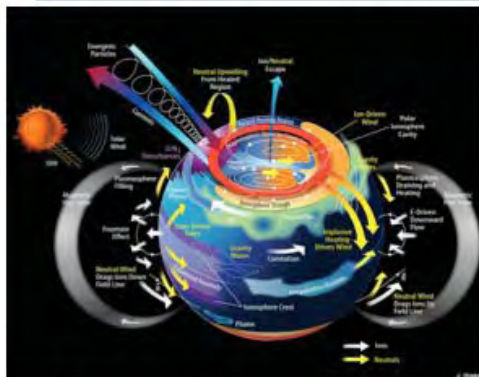
F4, H1, H4, J2

Enabling and Enhancing Technology Development:

- Precision formation flying with low-mass, efficient propulsion
- Optics control and beam combining with ~5nm precision
- Integration and test of many-element, long baseline distributed aperture system
- Mass-production of lightweight, UV-quality mirrors



Storm-Time Observations by Remote and In Situ Measurements



STORM Science Objectives:

- **Science/Exploration:** How does the upper atmosphere respond to forcing from above and below? What are the important drivers? What physics is missing in the ITM models that prevents us from having a real understanding or a predictive capability?
- **Programmatic:** This mission addresses key LWS objectives of understanding storm-time response for DoD and DoC customers and addresses some of the key STP science issues as well.

Associated RFAs: F2, F3, F4, H1, H2, H3, H4, J4

Mission Implementation Description:

- 3 FUV sensors at GEO, 2 small satellites in LEO, 4 microsats in LEO, 4 microsats in eccentric orbits for in situ density and drag measurements, hypersonic vehicle (optional) for focused investigations.
- all satellites are 3-axis controlled but have different purposes and requirements
- FUV imagers at geo, ion density and drift measurements (in situ) from LEO, density and energetics observations from fixed LST and variable LST orbits. All have high TRL.

Measurement Strategy:

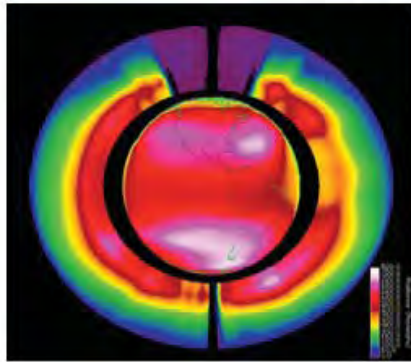
Don't try to do everything from one platform – use the right tool for the job!

Enabling and Enhancing Technology Development:

- Micro satellites with 3 axis stabilization
- Miniature cryocoolers
- Solar blind detectors
- Hypersonic vehicles



Thermosphere Ionosphere Global and Regional Imaging in Space and Time



TIGRIST Science Questions:

- (1) What is the prompt global-scale ionospheric response to geomagnetic storms?
- (2) What is the extended response of the thermosphere and the global scale ionosphere to geomagnetic storms?
- (3) How do traveling ionospheric disturbances develop and propagate?
- (4) What affects the day to day variability of equatorial ionosphere?
- (5) What are the temporal and spatial properties of high latitude I-T upflows and out flows?

Associated RFAs: F2, F3, H1, H2, J4

Mission Implementation Description:

***Concept:** The TIGRIST payload will be "piggybacked" on a commercial communications satellite over the western hemisphere. The launch services and spacecraft accommodations will be managed through the GEO Quick Ride program and the Goddard Space Flight Center (GSFC).

***Instruments:** (1) Steerable FUV/EUV regional scale imager (RSI) at 83.4 nm, 130.4 nm, 135.6 nm, and 155.0 nm with a spatial resolution of 4 km and 1000x1000km FOV. (2) Fixed FUV full disk global scale imager (GSI) 135.6 nm and 155.0 nm with a resolution of 30 km.

***Payload resources required (mass/pwr/tlm):** 109.6kg (30% margin)/99.8W (30% margin)/1.0 Mb/s (maximum)

***Measurement Strategy:** GSI images Ne dayside, Ne and O/N2 on limb dayside and high resolution regional Ne on nightside. GSI images full disk O/N2 on dayside and full disk Ne on nightside

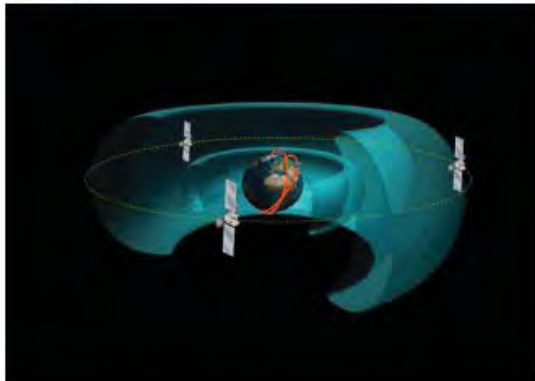
Enabling and Enhancing Technology Development:

All required technologies are currently available to perform the TIGRIST baseline mission, however technology development will increase the value of the retrieved data.

1. Development 83.4 nm filter coatings to enhance rejection of undesirable spectral lines



Thermosphere Ionosphere Storm Observatory



Science Objectives:

Determine how the thermosphere-ionosphere responds to forcing from above and from below

1. Understand how geomagnetic storms alter the structure of the thermosphere and ionosphere
2. Understand the global response of the thermosphere-ionosphere to solar extreme-ultraviolet variability
3. Determine the global tidal structure and response to atmospheric waves

Associated RFAs:

F3, H2, J4

Mission Implementation Description:

- Number of spacecraft: 3 GEO + 1 LEO
- Number of instruments: 3 GEO + 2 at LEO
- Types of instruments:
 - GEO: Remote sensing UV imager, TRL ≥ 6
 - LEO: In-situ plasma/neutral parameters, TRL ≥ 6
- Payload resources at GEO: 30 kg/30 W/5.0 Mbps
- Spacecraft:
 - GEO: Low-cost ride on commercial comsat
 - LEO: Pegasus-class, high-inclination

Enabling Technology Development:

- Accommodation on commercial communications satellite with real-time data capability
- Advanced development of delay-line UV detectors

Measurement Strategy:

- Simultaneous global imaging of temperature and atomic/molecular composition ratio during the day
- Comprehensive global imaging of peak electron density during night
- High-resolution measurements of low-latitude ionospheric irregularities at night
- Limb measurements of neutral composition altitude profiles and exospheric temperature
- Ability to distinguish tidal and storm effects as a function of both local time and longitude
- LEO satellite provides measurements of auroral energetics and plasma-neutral interactions



Tropical Atmosphere/Ionosphere/Thermosphere Coupler



TRAIT Science Objectives:

- Determine energy deposition from the low and middle atmospheric sources, such as tropical storm systems, into the Earth's upper atmosphere and ionosphere.
- Determine the neutral and electro-dynamical coupling between the Earth's low latitude mesosphere, thermosphere, ionosphere, and inner plasmasphere.

Associated RFAs:

F2.4, F3.1, F3.4, H2.3, J4.4

Mission Implementation Description:

*Number of spacecraft: 2

*Location: LEO with low inclination ($< 20^\circ$): 2 with elliptical orbits (250 x 1500 km) Apogees: 180° apart, Perigee: dipping as low as 150 km

*Attitude control: All spacecraft three-axis stabilized, momentum biased at 1 RPO

*Instrumentation: Combination of in-situ and remote sensing instrumentation suite. TRL ≥ 8 for all instruments.

*Payload resources: 2 S/C, payload adapter, prop sys, and fuel: approx. 1400 kg

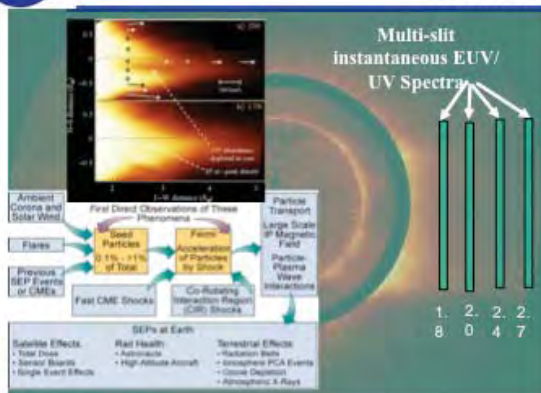
Measurement Strategy: The two dipping satellites provide investigations of vertical coupling through continuous coverage in each orbit. Remote sensing: gravity waves, airglow, neutral winds, plasma density. In-situ: electric fields, magnetic fields, thermal, energetic plasma, neutral density, winds, lightning

Enabling and Enhancing Technology Development:

- No "Enabling" technology required.
- New enhancing technology should reduce spacecraft cost by 10%.



UV Spectro-Coronagraphic Observations of Solar Energetic Particle Related Phenomena



Mission Implementation Description:

- Atlas, 650 km Sun-synchronous (~ 98.6 degrees) orbit
- 3-axis stabilized, Sun-pointing, Solar array powered
- EUV/UV imaging multi-slit spectro-coronagraph
- White light imaging coronagraph
- Payload mass: 250 Kg, Power: 150 W, Data Rate: 10 Mbps

Technology Development:

- Mission can be accomplished with no new technology.
- Mission requires smaller pathfinder missions to identify key observables for measuring the suprathermal seed population distribution and the impact of the CME shock on the coronal material.

Measurement Strategy:

- Observe with externally occulted EUV/UV and WL coronagraphs the spatial distribution of temperature, outflow velocity (via Doppler dimming) and Line-of-sight Doppler velocity, intensity, and density of multiple ions and electrons in the corona from 1.5 to 6 Solar radii.
- Provide high resolution EUV/UV spectral line profiles of ions with various charge to mass ratios including OVI, He II, H, and other species with bright resonance scattering simultaneously at multiple heights in the corona.
- Provide spectral profiles of the non-thermal distribution of OVI, He II, and H due to suprathermal particles.

Appendix G—Acronyms

